SCIENCE AND TECHNOLOGY

JET PROPULSION

Journal of the

AMERICAN ROCKET SOCIETY

Rocketry . . . Jet Propulsion Sciences . . . Astronautics

VOLUME 26 SEPTEMBER 1956 NUMBER 9

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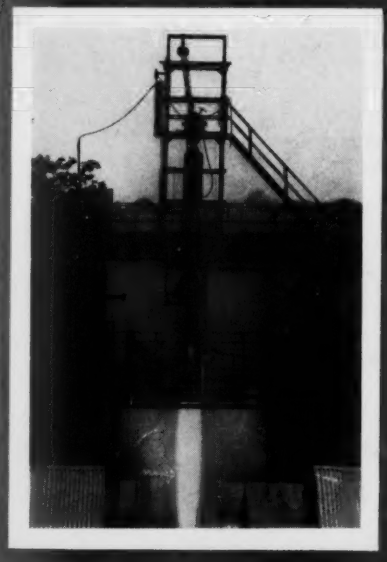

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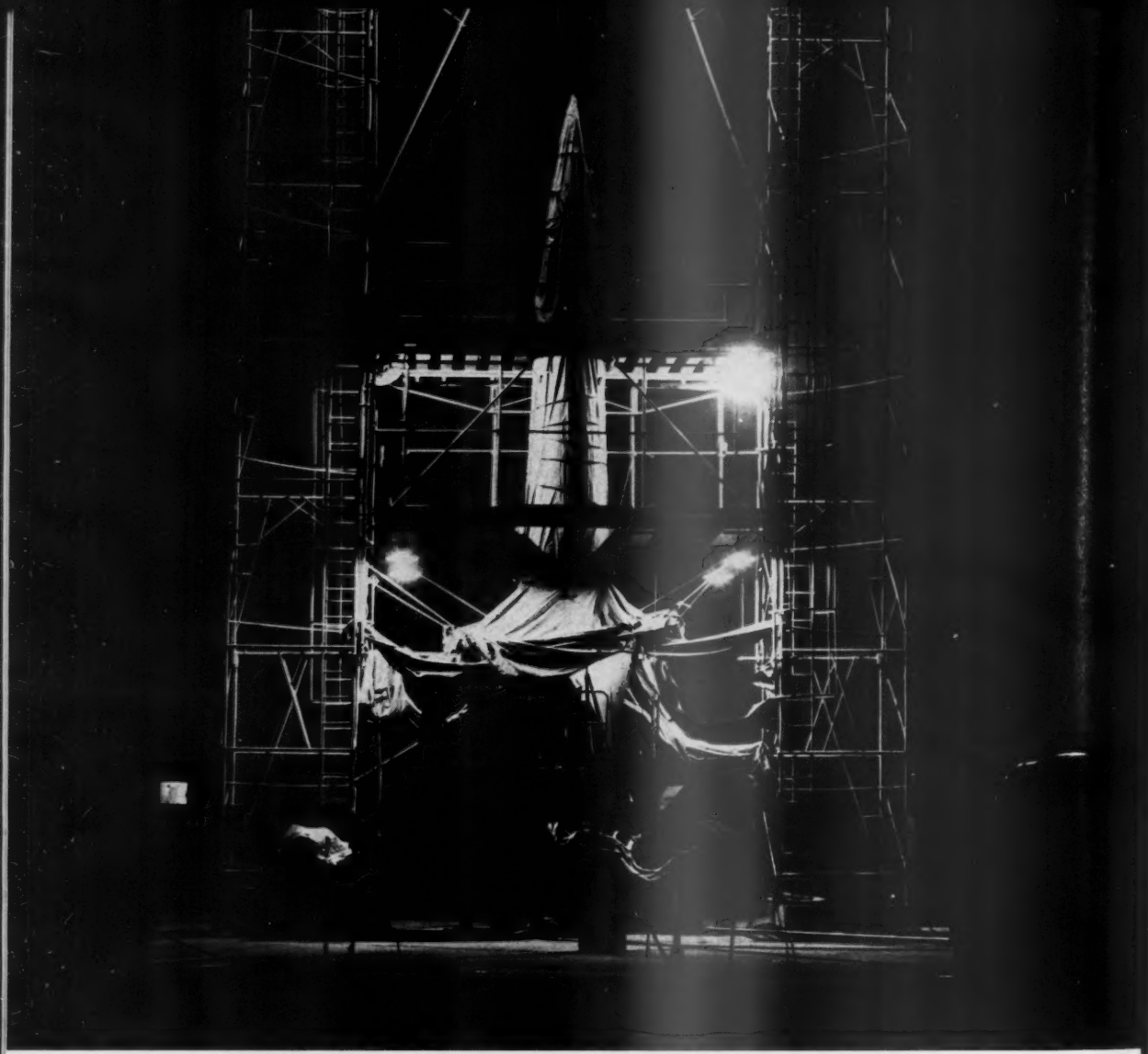

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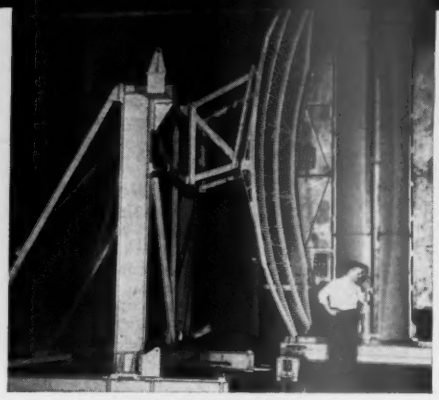

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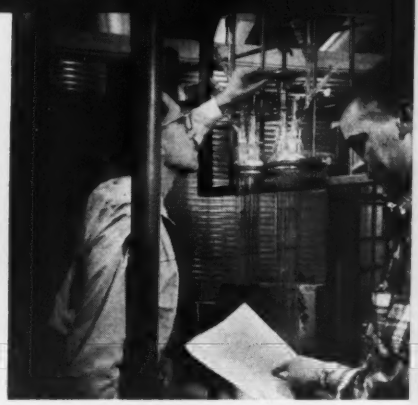

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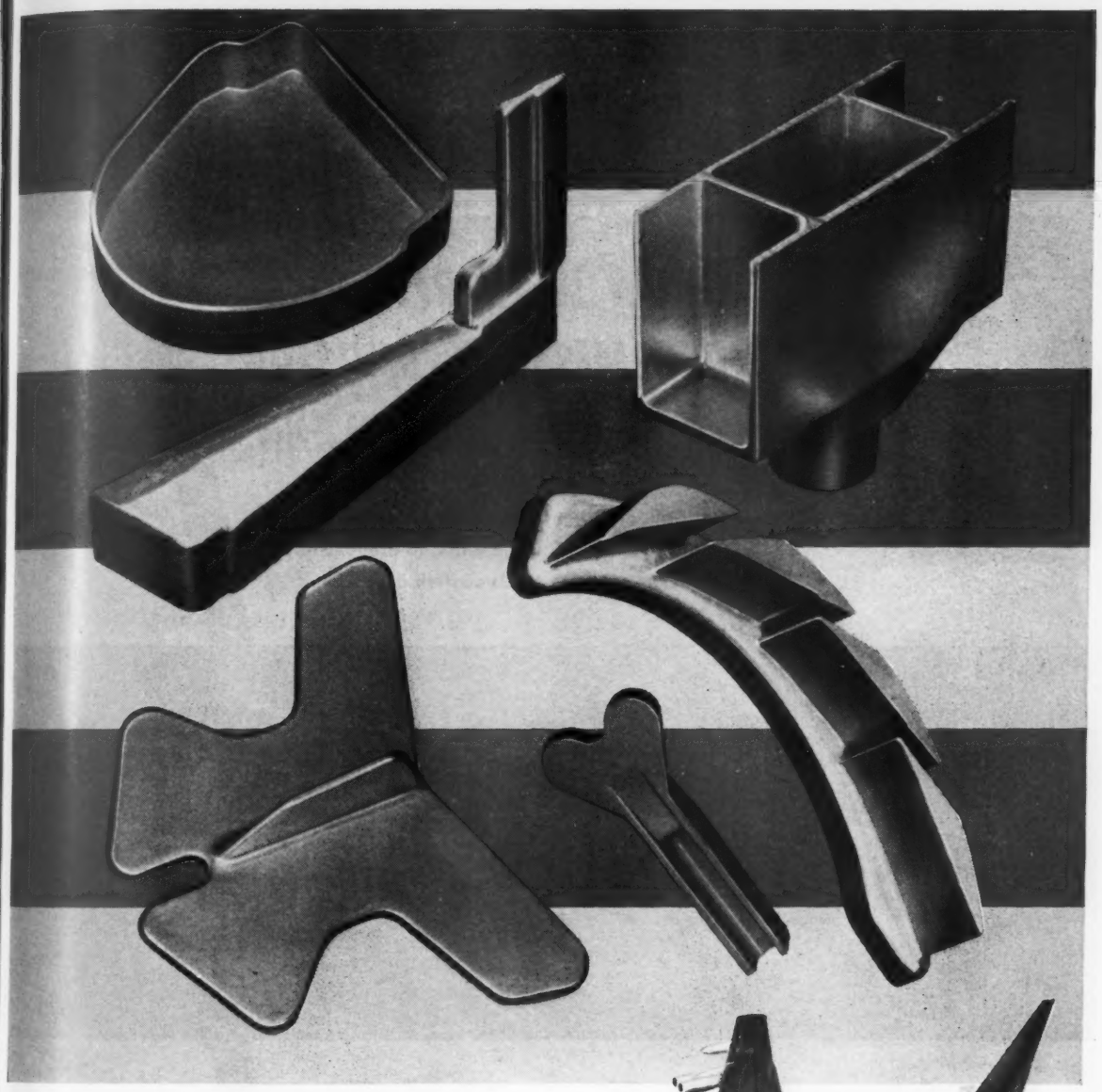

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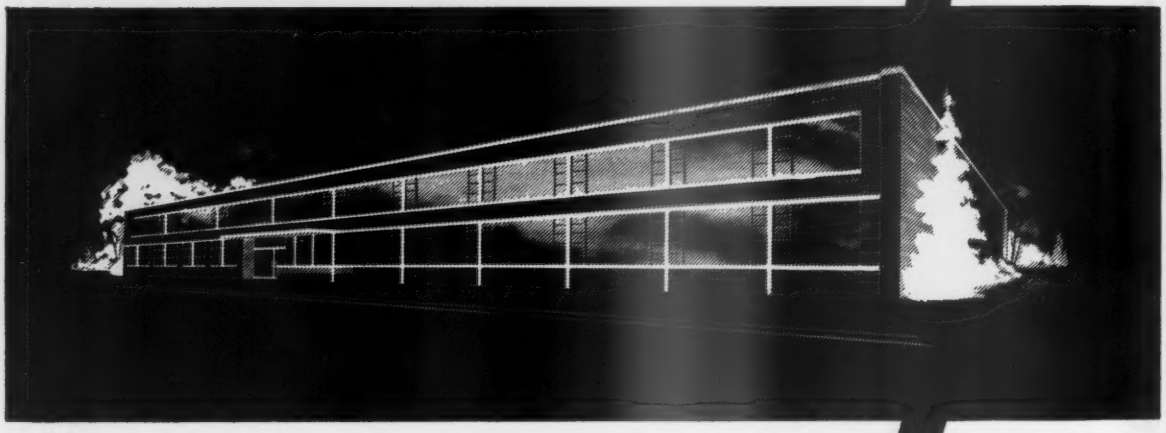

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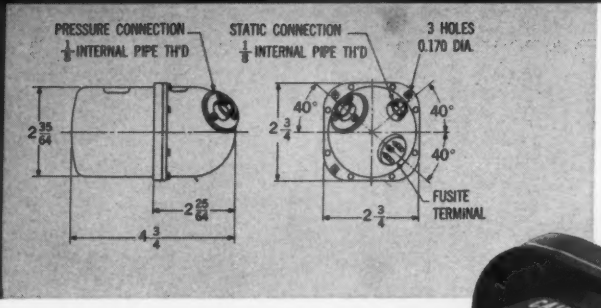

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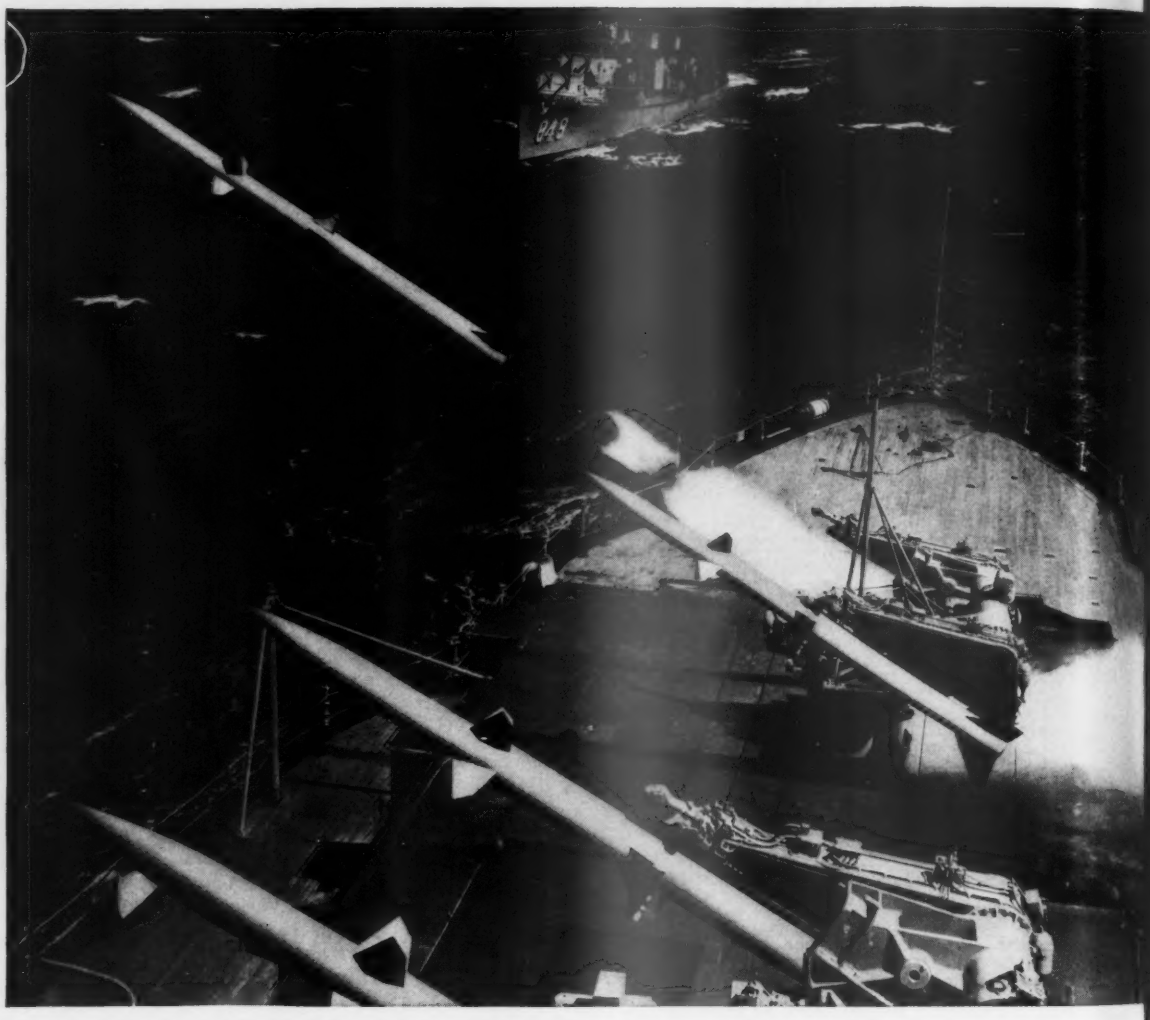

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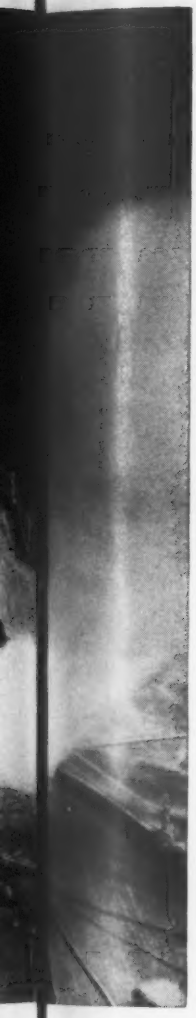

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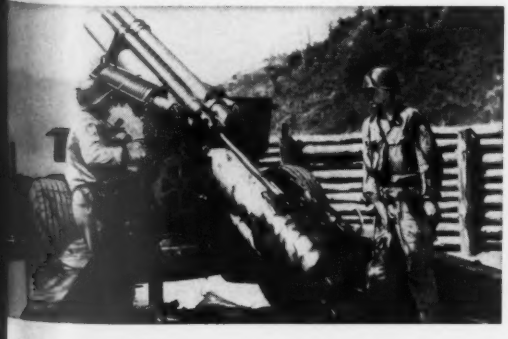

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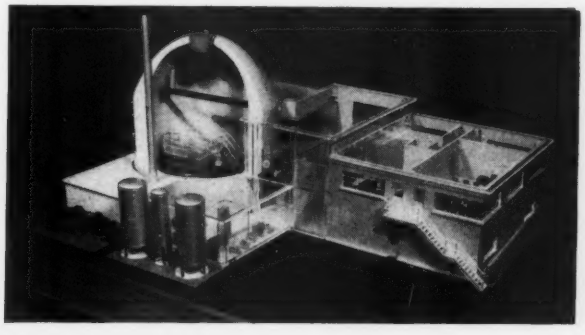

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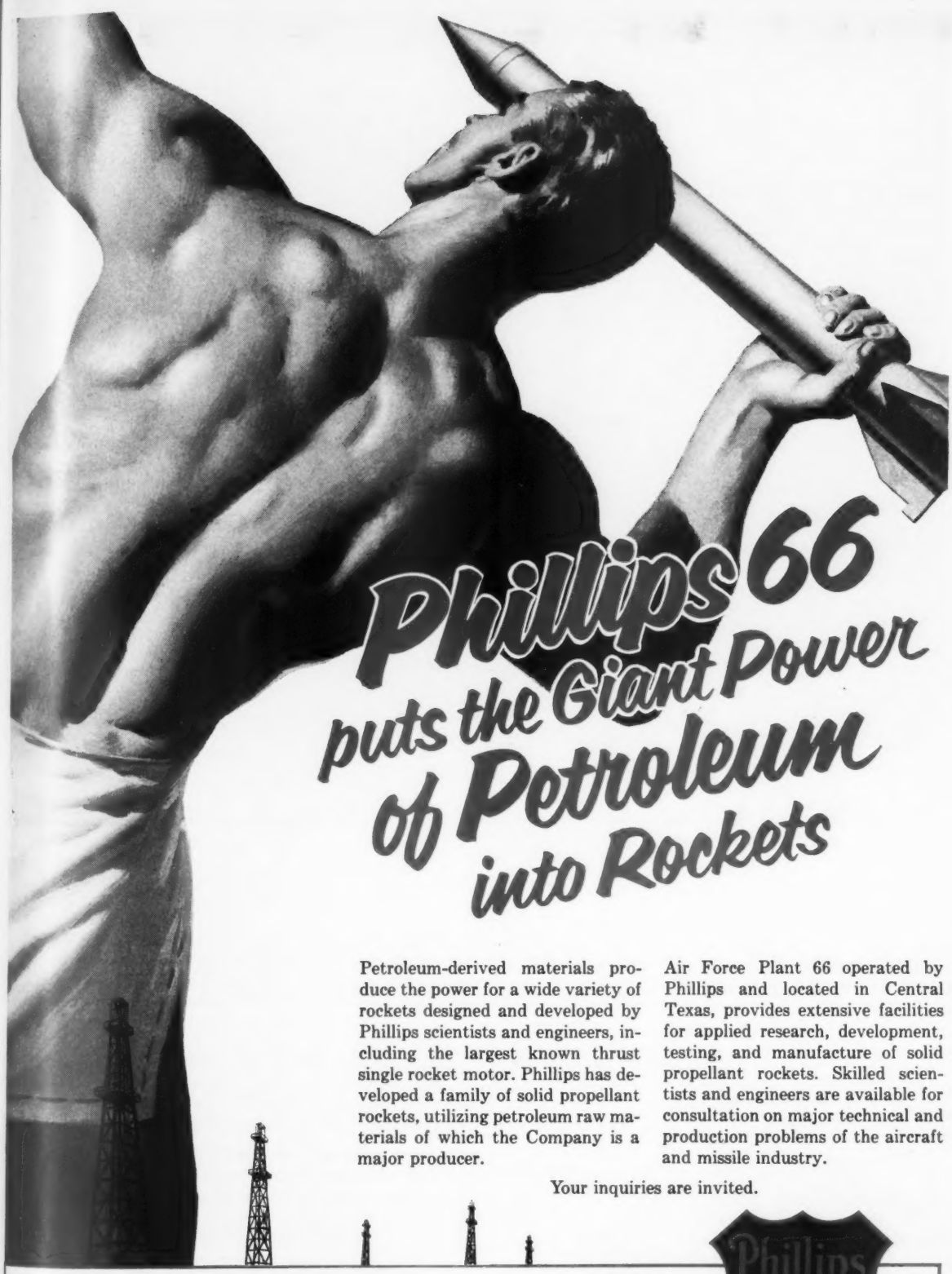

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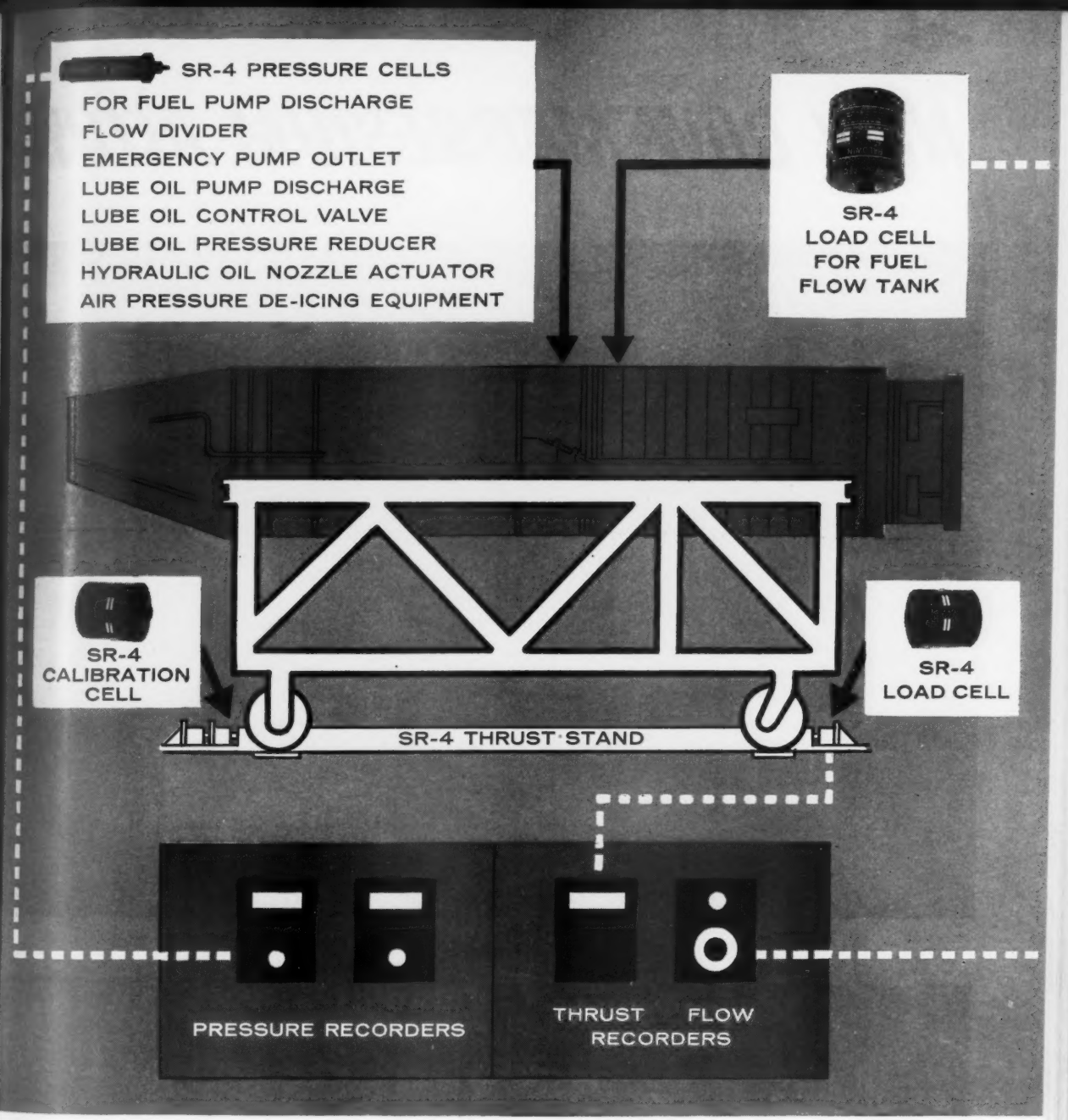

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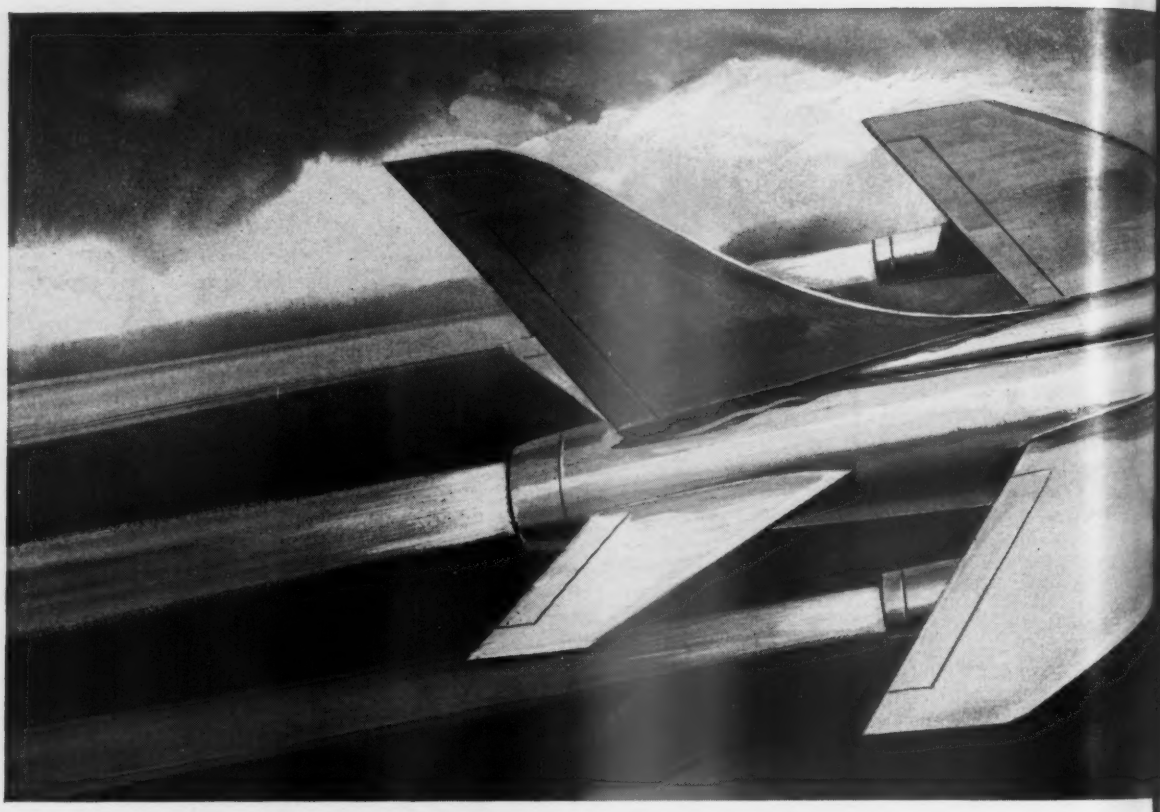
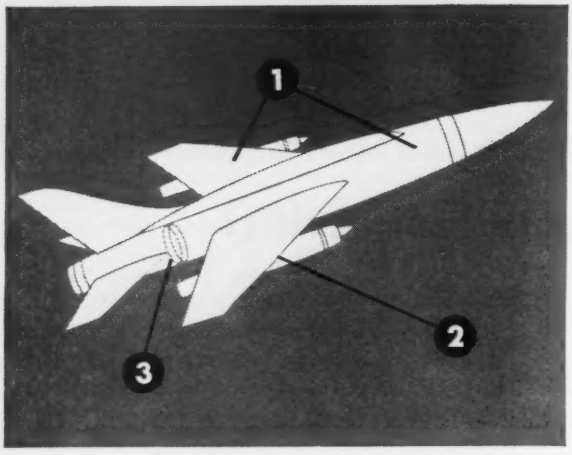
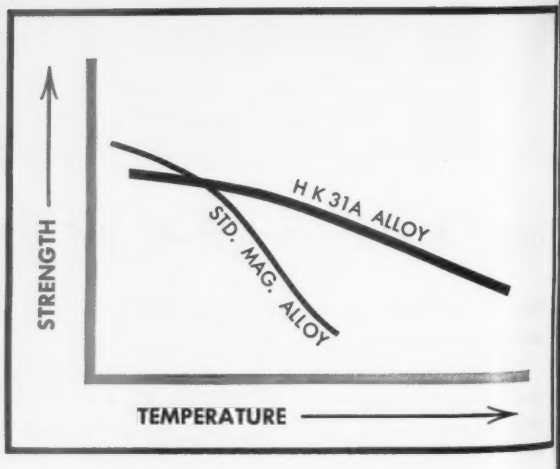




Now suggested *for a broad range of uses in missiles and aircraft, the new Dow magnesium alloys are available in the form of (1) sheet or plate, (2) extrusions, (3) castings.*



Maintenance of strength *at high temperatures is illustrated by this chart. Performance data on the new alloys at elevated temperatures can be obtained by request.*

DOW

...S CRACK HEAT BARRIER!

High temperature magnesium alloys are available to lighten aircraft and missile structures

Once again the horizons for aircraft structural design have been widened. Dow has developed a series of high temperature magnesium alloys which are already in pre-production use on aircraft, missile and engine structures. These alloys show advantages at temperatures up to 700° F. Limited test data on properties up to 800° F. are available for some of these alloys.

The new alloys save precious pounds because of their good combination of modulus and properties, including creep strength, at temperature. Shop characteristics include good formability and weldability.

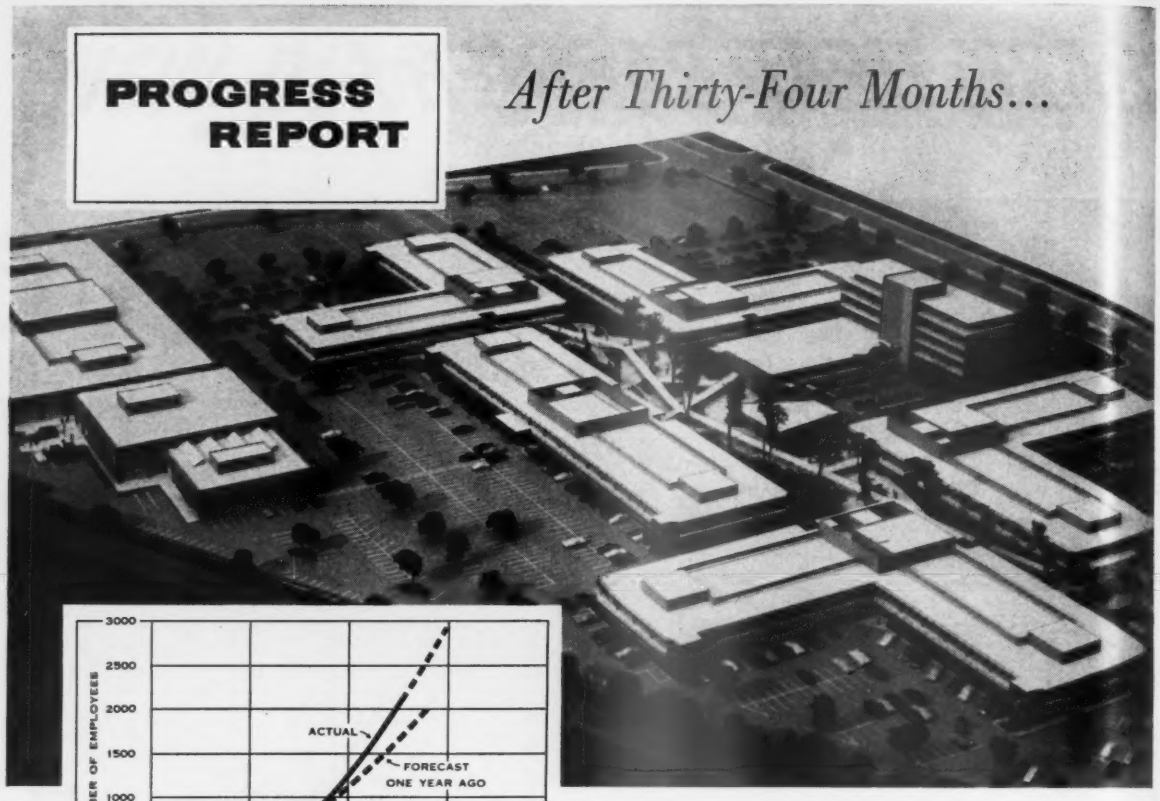
One of the available alloys is the magnesium-thorium composition, HK31A, which is manufactured in rolled and cast form. Under development is a similar alloy for extruded shapes and forgings. HK31A sheet and plate are available from stock and from current mill delivery schedules in standard sizes from 0.016″ to 2″.

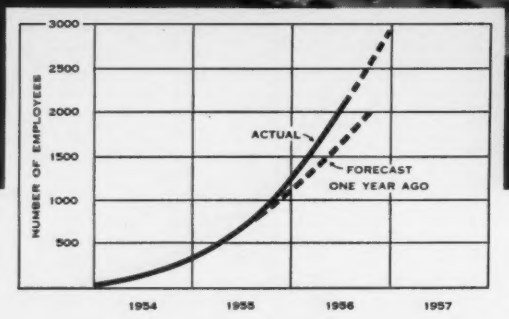
These new magnesium alloys by Dow should be considered for your high temperature requirements. Contact your nearest Dow sales office or write THE DOW CHEMICAL COMPANY, Magnesium Sales Dept., MA 361GG, Midland, Michigan.

you can depend on DOW MAGNESIUM DOW

PROGRESS REPORT

After Thirty-Four Months...





RESEARCH AND DEVELOPMENT PERSONNEL The above curve shows the growth in Ramo-Wooldridge personnel which has taken place since our Progress Report one year ago. A significant aspect of this growth is the increase in our professional staff which today is made up of 135 Ph.D.'s, 200 M.S.'s and 265 B.S.'s or B.A.'s. Members of the staff average approximately ten years' experience.

FACILITIES Within the past few months, construction has been completed at our Arbor Vitae complex, which now consists of eight modern buildings of 350,000 square feet, four of which are illustrated at the bottom of the page. Nearby is the R-W flight test facility, including hangar, shop, and laboratories, located on a 7-acre plot at International Airport.

To provide additional space for our continuing growth, construction has been started on an entirely new 40-acre Research and Development Center, located three miles from the Arbor Vitae buildings. The photograph above is of a model of the Center, which we believe will be one of the finest research and development facilities in the country. The first three buildings, now under construction, will total 250,000 square feet.

A second major construction program is underway on a manufacturing plant for quantity production of electronic systems. The initial unit of the plant, located on a 640-acre site in suburban Denver, Colorado, will be completed next spring and will contain approximately 150,000 square feet.

PROJECTS Our current military contracts support a broad range of advanced work in the fields of modern communications, digital computing and data-processing, fire control systems, instrumentation and test equipment. In the guided missile field, Ramo-Wooldridge has technical direction and systems engineering responsibility for the Air Force Intercontinental and Intermediate Range Ballistic Missiles. Our commercial contracts are in the fields of operations research, automation, and data processing. All this development work is strengthened by a supporting program of basic electronic and aeronautical research.

THE FUTURE *As we look back on our first three years of corporate history, we find much to be grateful for. A wide variety of technically challenging contracts have come to us from the military services and from business and industry. We have been fortunate in the men and women who have chosen to join us in the adventure of building a company. We are especially happy about the six hundred scientists and engineers who have associated themselves with R-W. Their talents constitute the really essential ingredient of our operations. We plan to keep firmly in mind the fact that the continued success of The Ramo-Wooldridge Corporation depends on our maintaining an organizational pattern, a professional environment, and methods of operating the company that are unusually well suited to the special needs of the professional scientist and engineer.*

The Ramo-Wooldridge Corporation

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Use of the Shock Tube Wall Boundary Layer in Heat Transfer Studies

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The temperature rise induced in the wall of a shock tube upon passage of the shock wave provides a useful technique for study of boundary layer characteristics in gases at extremely high temperatures, including dissociation. The boundary layer developed on a plane surface due to passage of the shock wave is inherently different from the usual boundary layer; however, it can be studied analytically and experimentally under relatively well-controlled conditions. It thus yields a convenient device for testing theories of the boundary layer under severe heat transfer and shear stress conditions.

Nomenclature

c_p = heat capacity at constant pressure
C = a thermal capacity
h = enthalpy
h = h/u_∞^2
H = $-\frac{1}{\sigma}\frac{dh}{d\bar{u}}u_\infty^2$
k = thermal conductivity
M_∞ = Mach number of shock wave
P = pressure
q = heat transfer rate per unit area
R = a thermal resistance
s = parameter in Laplace transform
T = absolute temperature
$\bar{T}$ = Laplace transform of T
u = velocity parallel to wall
$\bar{u}$ = u/u_∞
$\bar{u}_0$ = $\bar{u}$ behind shock wave = ρ_∞/ρ_0
U = u-dependent factor of shear stress τ
$\bar{U}$ = $\bar{U}/(u_\infty\sqrt{(\rho\mu)u_\infty})$
v = velocity normal to wall
x = coordinate parallel to wall
X = x-dependent factor of shear stress τ
y = coordinate normal to wall
γ = ratio of specific heats, c_p/c_v
δ = film thickness
η = fraction of equilibrium wall temperature
μ = viscosity
ρ = density
$\overline{\rho\mu}$ = $\rho\mu/(\rho\mu)_1$
σ = Prandtl modulus, $\mu c_p/k$
τ = shear stress

Subscripts

0 = refers to free stream conditions in gas behind ($\bar{u} = \bar{u}_0$) shock wave (high pressure side)
∞ = refers to (or relative to) undisturbed gas ahead of shock wave
1 = refers to wall conditions behind shock ($\bar{u} = 1$)
s = refers to solid wall

Received May 1, 1956.
[1] Head, Analysis Dept., Hypersonics R. & D. Staff.

Introduction

THE moving boundary layer developed behind the shock wave on the plane wall of a shock tube controls the transfer of momentum and heat to the wall. It differs from the usual (stationary) boundary layer in that it may be considered as having a relatively low "free stream" velocity and a high (*not zero*) velocity at the plane wall. In spite of the basic difference, the shear stress and heat transfer vary with distance from the "leading edge" in the same manner as in the stationary case. This fact leads to an extremely simple form for the time variation of temperature on the surface of the wall and thus to an interesting method for study of the boundary layer. In the following presentation, the theory of the boundary layer is developed first. The temperature history of the wall surface then follows, including a discussion of applications; finally the shear stress and wall heat transfer are determined for the special case of Prandtl modulus equal to one and product of gas density and viscosity constant across the boundary layer.

The analysis presented here was developed as a result of discussions with Walker Bleakney and some of his co-workers at Princeton University who have observed these phenomena in the shock tube. Some of their results are now available; see (5).[2] Work along similar lines has been or is in progress at other institutions; see (2, 3, and 4).

The Boundary Layer Equations

The flow of gas in the immediate vicinity of the shock wave in a shock tube may be described conveniently in a reference frame moving with the wave. Under these conditions the profiles of temperature, velocity, and shear stress are stationary (do not vary with time). In the presentation following, reference may be made to Fig. 1.

Writing the boundary layer equations in the form used by Crocco (1) for a flat plate with zero pressure gradient, where x and u (the x component of velocity) are the independent variables and the shear stress

$$\tau = \mu\frac{\partial u}{\partial y}$$

(y is distance normal to wall) is the dependent variable in the momentum equation; we have

$$u\frac{\partial}{\partial x}\left(\frac{\rho\mu}{\tau}\right) + \frac{\partial^2\tau}{\partial u^2} = 0 \quad \ldots\ldots[1]$$

and

$$(1-\sigma)\frac{\partial h}{\partial u}\tau\frac{\partial\tau}{\partial u} + \left(\frac{\partial^2 h}{\partial u^2} + \sigma\right)\tau^2 - \sigma u\rho\mu\frac{\partial h}{\partial x} = 0 \quad \ldots[2]$$

for the momentum and energy relations, respectively. As in the usual flat plate case, we anticipate a solution where h is a

[2] Numbers in parentheses indicate References at end of paper.

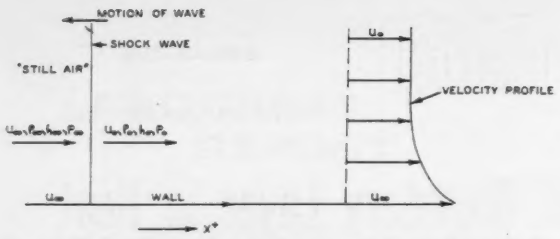

Fig. 1 Illustration of reference frame used showing how velocity profile would appear

function of u only. Then $\rho\mu$ is a function of h, and thus of u only, and we try a separation of variables solution

$$\tau = X(x) \cdot U(u)$$

This leads to the condition

$$\frac{1}{X^3}\frac{dX}{dx} = \frac{U}{\rho\mu u}\frac{d^2U}{du^2} = -1$$

The shear stress must be discontinuous at $x = 0$ so the solution of the X equation is

$$X = 1/\sqrt{2x}$$

The U equation, yet to be solved, is

$$U \cdot (d^2U/du^2) + \rho\mu u = 0$$

subject to the boundary conditions

$$dU/du = 0 \text{ at } u = u_\infty \qquad U = 0 \text{ at } u = u_0$$

Letting

$$u/u_\infty = \bar{u} \qquad \overline{\rho\mu} = \rho\mu/(\rho\mu)_1$$

and

$$U/\left(u_\infty \sqrt{(\rho\mu)_1 u_\infty}\right) = \bar{U}$$

the equation for U may be written

$$\bar{U} \cdot (d^2\bar{U}/du^2) + \overline{\rho\mu}\bar{u} = 0 \quad \ldots\ldots\ldots\ldots [3]$$

subject to

$$d\bar{U}/d\bar{u} = 0 \text{ at } \bar{u} = 1 \qquad \bar{U} = 0 \text{ at } \bar{u} = \bar{u}_0$$

The shear stress is thus

$$\tau/u_\infty = \left(1/\sqrt{2x}\right) \cdot \bar{U}\sqrt{(\rho\mu)_1 u_\infty} \quad \ldots\ldots\ldots\ldots [4]$$

and at the wall it is

$$\tau(1)/u_\infty = \left(1/\sqrt{2x}\right) \cdot \bar{U}(1)\sqrt{(\rho\mu)_1 u_\infty} \quad \ldots\ldots\ldots [5]$$

The energy equation may now be expressed as

$$(1 - \sigma)\frac{dh}{d\bar{u}}\frac{d \ln \bar{U}}{d\bar{u}} + \frac{d^2h}{d\bar{u}^2} + \sigma = 0 \quad \ldots\ldots\ldots [6]$$

where $h = h/u_\infty{}^2$ and the equation is subject to $h = h(1)$ at the wall;[3] $h = h(\bar{u}_0)$ in the free stream.

It should be noted that except for the different boundary condition at the wall, the differential equations and general mode of solution (included here for the sake of completeness) are identical to the case of the usual flat plate boundary layer.

We shall defer the solution of Equations [3] and [6] until a later section, noting here that the heat transfer rate at the wall will be

$$\dot{q}_1 = -k\left.\frac{\partial T}{\partial y}\right|_1 = -\frac{1}{\sigma}\mu\left.\frac{\partial h}{\partial y}\right|_1 = -\frac{1}{\sigma}\tau\left.\frac{dh}{du}\right|_1$$

$$= \frac{\bar{U}}{\sqrt{2x}}\sqrt{(\rho\mu)_1 u_\infty}\left(-\frac{1}{\sigma}\left.\frac{dh}{d\bar{u}}\right|_1\right)u_\infty{}^2 \quad \ldots [7]$$

The Temperature Response of the Wall

Subject to the conditions implicit in the derivation of the previous section (in particular that the gas properties are functions only of u), the heat transfer rate at a fixed point on the wall of the shock tube is

$$\dot{q} = -\left(\frac{1}{\sigma}\frac{dh}{d\bar{u}}u_\infty{}^2\right)_1 \bar{U}(1)\sqrt{\frac{(\rho\mu)_1 u_\infty}{2u_\infty t}}$$

where we have inserted $x = u_\infty t$, and t is the time measured from the passage of the shock wave. Then letting

$$-\left(\frac{1}{\sigma}\frac{dh}{d\bar{u}}u_\infty{}^2\right)_1 = \bar{H}(1)$$

we have

$$\dot{q} = \bar{H}(1) \cdot \bar{U}(1)\sqrt{\frac{(\rho\mu)_1}{2t}} \quad \ldots\ldots\ldots\ldots [8]$$

For the short times of interest here (of the order of 100 microsec), any ordinary wall thickness will appear as a semi-infinite slab with respect to heat conduction effects. We shall therefore examine the effects of the heat input function of Equation [8] on a semi-infinite slab.[4] Transforming the diffusion equation for the slab using the Laplace transform, the solution for the temperature of the surface in transform form is

$$\bar{T} = \frac{1}{\sqrt{s}}\frac{L(\dot{q})}{\sqrt{kc_p\rho}}$$

where

k = thermal conductivity of slab
c_p = heat capacity of slab
ρ = density of slab
$L(\dot{q})$ = the Laplace transform of $\dot{q}$

The transform needed is

$$L(\dot{q}) = \bar{H}(1) \cdot \bar{U}(1)\sqrt{\frac{(\rho\mu)_1 \pi}{2s}}$$

and

$$\bar{T} = \frac{1}{s}\bar{H}(1)\bar{U}(1)\sqrt{\frac{\pi(\rho\mu)_{1,\text{ gas}}}{2(kc_p\rho)_{1,\text{ solid}}}}$$

The inverse transform of this is a step function. In other words, if the heat input function is as given by Equation [8], the wall temperature rises instantly to

$$t_1(0^+) = \bar{H}(1)\bar{U}(1)\sqrt{\frac{\pi(\rho\mu)_{1,\text{ gas}}}{2(kc_p\rho)_{1,\text{ solid}}}} \quad \ldots\ldots\ldots [9]$$

and remains at this value as long as the conditions postulated exist. We thus have an interesting method for measuring the character of the U function, and thus of the associated heat transfer and skin friction phenomena.

Two important characteristics of any real situation have been omitted in the above:

1 The effect of the deviation from the semi-infinite slab condition in the measuring instrument.

2 Time (and thus distance) dependence of gas properties behind the shock due to deviation from equilibrium conditions. The finite time necessary for dissociation and recombination might thus cause a time variation in the wall temperature.

We shall consider these cases separately.

[3] As will be seen in the next section, $h(1)$ at the wall should be the value after passage of the shock wave.

[4] We are then neglecting any conduction effects in the solid in the direction parallel to the flow. See (3). The effect of parallel conduction was investigated separately by G. F. Carrier in a private communication to the author and shown to be small in typical applications.

1 *Effect of a Small Discrete Capacitance at the Surface of the Slab*

If a thin metallic layer of a good thermal conductor (as a resistance thermometer, for example) is deposited on a poor conductor, such as glass or a plastic, a reasonable approximation to the effect produced is given by consideration of a discrete resistance capacitance element placed on the surface. If we let

$$C = c_p\rho\delta \text{ of the metal film}$$
$$R = \delta/k \text{ of the metal film}$$
$$\delta = \text{thickness of the film}$$

then the diffusion "time constant" is

$$t_d = RC = \delta^2\cdot(c_p\rho/k)$$

For a very thin metal film of say gold or platinum, this time is so small that it may be neglected. For example, a layer of gold 500 A thick has a time constant of

$$t_d = \frac{500^2\cdot(10^{-8})^2\cdot 41.5\cdot 3600}{30.5^2\cdot 170} = 2.36\cdot 10^{-11} \text{ sec}$$

We shall therefore consider the effect of a pure capacitance (thin film) placed on the semi-infinite slab. Then

$$\dot{q} = C\cdot(dT/dt) + \dot{q}_{\text{slab}}$$

In transform form

$$L(\dot{q}) = Cs\bar{T} + \sqrt{kc_p\rho}\,\bar{T}$$

or

$$\bar{T} = \frac{1}{\sqrt{kc_p\rho}s}\,\frac{L(\dot{q})}{1 + (C/\sqrt{kc_p\rho})\sqrt{s}}$$

Compared to the case with C zero, we have a term

$$\frac{1}{s}\cdot\frac{1}{1 + (C/\sqrt{kc_p\rho})\sqrt{s}}$$

instead of $1/s$. The inverse transform is now, instead of 1

$$\eta = 1 - \exp(kc_p\rho t/C^2)\operatorname{erfc}c\sqrt{kc_p\rho t/C^2} \quad \ldots\ldots [10]$$

A sample calculation of the time parameter follows: Let the backing wall be quartz and use 500 A of gold

$$k_q = 0.55 \text{ Btu/(ft}^2\text{ °F/ft)}$$
$$c_{p_q} = 0.25 \text{ Btu/lb °F}$$
$$\rho_q = 168 \text{ lb/ft}^3$$
$$(c_p\rho)_{Au} = 0.034\cdot 1220 \text{ Btu/ft}^3\text{ °F}$$

$$\frac{c^2}{kc_p\rho} = \frac{(0.034\cdot 1220)^2\cdot(500\cdot 10^{-8})^2}{0.55\cdot 0.25\cdot 168\cdot 30.5^2}\cdot 3600 = 0.72\cdot 10^{-8} \text{ sec}$$

The function η is tabulated below for several values of the parameter $kc_p\rho t/C^2$

$kc_p\rho t/C^2$	η
0	0
1	0.1035
5	0.7667
9	0.8210
100	0.9439

For the time parameter large

$$\eta \cong 1 - [\pi kc_p\rho t/C^2]^{-1/2}$$

The time lag "error"[5] is therefore reduced directly as the capacity (film thickness).

[5] Note that this is not an error; the response may be computed and thus the measurement utilized.

[6] This form differs slightly from that used by Crocco and avoids the singularity difficulty at the upper limit.

It would appear that for rapid response the most critical item is the material of the metal film and the film thickness. A metal of low $c_p\rho$ must be used; of the metals that are feasible from other points of view, gold and platinum appear best.

2 *Effect of Time Dependence of Gas Properties*

Variation of the function U with distance results in a variation in heat input along the boundary layer not included in Equation [9]. In general we might let

$$\dot{q} = f(t)\,\frac{1}{\sqrt{\pi t}}\,\sqrt{kc_p\rho}$$

$$L(\dot{q}) = \int_0^\infty e^{-st}f(t)\,\frac{1}{\sqrt{\pi t}}\,dt\cdot\sqrt{kc_p\rho}$$

and

$$\bar{T} = \frac{1}{\sqrt{s}}\int_0^\infty e^{-st}f(t)\,\frac{1}{\sqrt{\pi t}}\,dt$$

for the simple semi-infinite slab situation. Then, if $f(t)$ is finite for all t and approaches a constant as $t \to \infty$, we may write

$$\bar{T} = \frac{f(\infty)}{s} - \frac{1}{s}\int_0^\infty \operatorname{erf}\sqrt{st}\; d(f(t))$$

and

$$T = f(\infty) - L^{-1}\left[\frac{1}{s}\int_0^\infty \operatorname{erf}\sqrt{st}\; df\right] \quad \ldots\ldots [11]$$

Equation [11] must be inverted for particular cases, yielding the function $f(t)$.

Solution of the Boundary Layer Equations

We now proceed to a discussion of the solution of the boundary layer Equations [3] and [6]. First, integrating Equation [3] (momentum) with respect to the velocity parameter $\bar{u}$

$$\frac{d\bar{U}}{d\bar{u}} - \left.\frac{d\bar{U}}{d\bar{u}}\right|_1 + \int_1^{\bar{u}} \frac{\overline{\rho\mu}\bar{u}'}{\bar{U}(\bar{u}')}\,d\bar{u}' = 0$$

but

$$\left.\frac{d\bar{U}}{d\bar{u}}\right|_1 = 0$$

Multiplying through by $\bar{U}(\bar{u})$ yields

$$\frac{d\bar{U}^2}{d\bar{u}} + 2\bar{U}\int_1^{\bar{u}} \frac{\overline{\rho\mu}\bar{u}'}{\bar{U}(\bar{u}')}\,d\bar{u}' = 0$$

and integrating again[6]

$$\bar{U}^2(\bar{u}) - \bar{U}^2(1) + 2\int_1^{\bar{u}} \bar{U}(\bar{u}'')d\bar{u}'' \int_1^{\bar{u}''} \frac{\overline{\rho\mu}(\bar{u}')}{\bar{U}(\bar{u}')}\,\bar{u}'d\bar{u}' = 0 \ldots [12]$$

where $\bar{U}(\bar{u}_0) = 0$. This equation may be used in an iterative procedure to obtain the function $\bar{U}(u)$. It must be solved together with the energy Equation [6] in order to evaluate the function $\bar{U}$. Equation [6] may be written (per Crocco)

$$\frac{d}{d\bar{u}}\left(\bar{U}^{1-\sigma}\frac{d\hbar}{d\bar{u}}\right) + \sigma\bar{U}^{1-\sigma} = 0 \quad \ldots\ldots [13]$$

This is integrated twice, yielding

$$\hbar(\bar{u}) = \hbar(1) + \left.\frac{d\hbar}{d\bar{u}}\right|_1 \bar{U}(1)^{1-\sigma}\int_1^{\bar{u}} \frac{d\bar{u}}{\bar{U}^{1-\sigma}} - \sigma\int_1^{\bar{u}} \frac{d\bar{u}''}{\bar{U}^{1-\sigma}}\int_1^{\bar{u}''} \bar{U}^{1-\sigma}\,d\bar{u}' \ldots [14]$$

Crocco noted that, in the usual flat plate case, $\hbar$ was quite insensitive to the dependence of $\bar{U}$ on $\rho\mu$, at least for σ close to

unity. We should expect the same effect here, thus eliminating the need for iteration on $\bar{h}$. That is, we may solve Equation [12] for the case $\overline{\rho\mu} = 1$, and use the resulting $\bar{U}$ in [13] to find the dependence of $\bar{h}$ on $\bar{u}$ and σ, using the resulting $\bar{h}$, in turn, in [12] for the various $\rho\mu$ laws and other boundary conditions.

Special Case of $\sigma = 1$ and $\overline{\rho\mu} = 1$

When $\sigma = 1$ and $\rho\mu = 1$, the equations are in their simplest form; it is instructive to examine this case in some detail and obtain the wall temperature rise.

For $\sigma = 1$, Equation [13] may be integrated immediately to yield

$$\left.\frac{d\bar{h}}{d\bar{u}}\right|_1^{\bar{u}} + \bar{u}\Big|_1^{\bar{u}} = 0$$

Integrating again to the limit $\bar{u} = \bar{u}_0$

$$\bar{h}\Big|_1^{\bar{u}_0} - \left.\frac{d\bar{h}}{d\bar{u}}\right|_1 \bar{u}\Big|_1^{\bar{u}_0} + \frac{\bar{u}^2}{2}\Big|_1^{\bar{u}_0} - \bar{u}\Big|_1^{\bar{u}_0} = 0$$

or

$$-\left.\frac{d\bar{h}}{d\bar{u}}\right|_1 = \frac{\bar{h}(\bar{u}_0) - \bar{h}(1) - \left(\frac{1-\bar{u}_0^2}{2}\right) + 1 - \bar{u}_0}{1 - \bar{u}_0}$$

In the coordinate system used (riding with the shock wave)

$$\bar{h}_\infty + {}^1/_2 = \bar{h}(\bar{u}_0) + (u_0^2/u_\infty^2)\cdot({}^1/_2) = \bar{h}(\bar{u}_0) + \bar{u}_0^2/2$$

and

$$\bar{h}(\bar{u}_0) = \bar{h}_\infty + (1 - \bar{u}_0^2)/2$$

Then

$$-\left.\frac{d\bar{h}}{d\bar{u}}\right|_1 = \frac{\bar{h}_\infty + \frac{1-\bar{u}_0^2}{2} - \bar{h}(1) - \frac{1-\bar{u}_0^2}{2} + 1 - \bar{u}_0}{1 - \bar{u}_0}$$

$$= 1 - \left(\frac{\bar{h}(1) - \bar{h}_\infty}{1 - \bar{u}_0}\right) \quad \ldots\ldots[15]$$

where $(\bar{h}(1) - \bar{h}_\infty)$ corresponds to the temperature increase at the wall. Note that the enthalpy gradient obtained here does *not* correspond to that for a boundary layer fixed with respect to a shock tube reference frame.

Equation [12] (for the shear stress function) has been solved for various values of $\bar{u}_0$; the value of $\bar{U}(1)$ is plotted in Fig. 2. As a matter of interest, the shear stress function $\bar{U}(\bar{u})$ is plotted in Fig. 3 for several values of $\bar{u}_0$.

For this case of a very high wave velocity in a perfect gas, Equation [9] may be approximated as follows (recalling that here $\sigma = 1$)

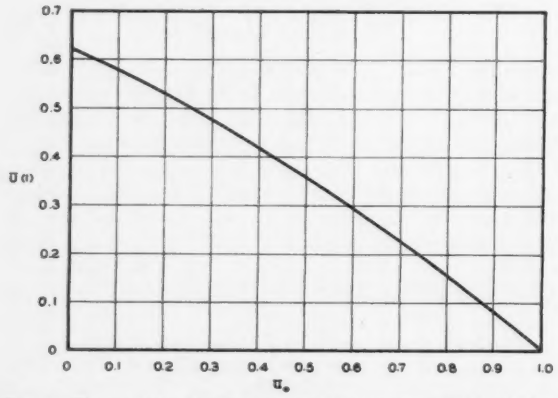

Fig. 2 Shear stress function evaluated at wall vs. fluid velocity relative to shock wave

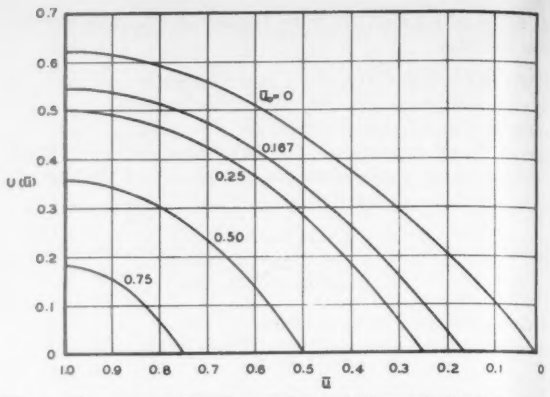

Fig. 3 Shear stress function vs. dimensionless velocity in boundary layer

$$\Delta t_{\text{wall}} = u_\infty^2 \bar{U}(1) \sqrt{\frac{\pi P_0(\rho\mu)_{\infty,\,\text{gas}}}{2P_\infty(kc_p\rho)_{1,\,\text{solid}}}} \left(1 - \frac{\Delta\bar{h}}{1 - \bar{u}_0}\right)$$

But

$$\frac{P_0}{P_\infty} = 1 + \frac{\rho_\infty u_\infty^2}{P_\infty}(1 - \bar{u}_0) \cong \frac{\rho_\infty u_\infty^2}{P_\infty}(1 - \bar{u}_0)$$

$$= \gamma_\infty M_\infty^2(1 - u_0)$$

and

$$\Delta t_{\text{wall}} \frac{c_p}{u_\infty^2} = \Delta\bar{h}$$

Then

$$\frac{\Delta t_{\text{wall}}}{T_\infty} = \frac{(\gamma - 1)\bar{U}(1)\sqrt{\frac{\pi}{2}\gamma(1 - \bar{u}_0)\frac{(kc_p\rho)_\infty}{(kc_p\rho)_1}}\, M_\infty^2}{1 + \frac{\bar{h}_\infty}{1 - \bar{u}_0}\,[\text{numerator}]} \quad \ldots[16]$$

As an example, a wave velocity of Mach 7 in air at 0.1 atm and 59 F would produce, on a quartz wall, a temperature rise of about 57 F.

Summary

It has been shown that by measuring the temperature rise on the wall of a shock tube, and correlating this rise with the moving shock wave boundary layer heat transfer, a useful analysis of the basic phenomena may be made. If the gas behavior behind the shock wave is "simple"—that is, such things as relaxation phenomena do not affect the flow—then the temperature of the wall rises instantaneously to a new equilibrium value and then remains constant. If, however, more complex phenomena govern, the effects will be immediately apparent in a nonconstant temperature versus time (distance from the shock wave).

The temperature rise obtained is relatively large for a strong shock, as much as several hundred degrees Fahrenheit on an insulating wall.

Also, although the boundary layer equations break down near the "leading edge," the effect on the over-all temperature history will be small for reasonably large flow times.

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Properties of Fuming Nitric Acid Affecting Its Storage and Use as a Rocket Propellant[1]

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Some of the general problems of storing fuming nitric acid (the system HNO_3–NO_2–H_2O) in closed metal containers for periods of the order of months at elevated temperatures around 130 F are discussed. A literature review of some of the properties of importance for satisfactory storage and use as a rocket propellant, as well as a discussion of chemical methods of analysis, is included. Two chemical processes which cause problems in the storage of this widely used oxidant are: (a) the corrosion of metal containers causing change in composition of the acid and its contamination with metallic salts, and (b) the thermal decomposition of acid lean in NO_2 and H_2O with accompanying high pressures and changes in composition of the oxidant. Liquid and gas phase corrosion of aluminum alloys and of stainless steel alloys of the 18–8 class are found to be markedly inhibited by the presence of about 0.5 wt per cent hydrofluoric acid in the fuming nitric acid, thus reducing the first problem of storage. The mechanism of passivation appears to be the formation of an impervious coating of insoluble metal fluoride on the surface of the metal. The second problem of thermal decomposition and correspondingly excessive storage pressures is eliminated in acid containing enough NO_2 (12 to 16 wt per cent) to obtain the results desired without causing high partial pressure of this species, and enough H_2O (2 to 3½ wt per cent) to give satisfactory results without unduly diluting the oxidizing power.

Introduction

THE purpose of this paper is to discuss some of the available data on properties of fuming nitric acid[3] related to problems of storage and handling. The discussion of factors affecting the storability of fuming nitric acid is presented in more detailed form elsewhere (1).[4] Limitations are imposed on the storage conditions of fuming nitric acid as a result of its corrosive action on metal containers and the thermal decomposition of this acid. The rate of corrosion of aluminum and steel alloys by fuming nitric acid is appreciable and presents a problem (2–10) in storing acid in containers made of these alloys for extended periods of time. Undesirable results of such storage are weakening of the metal, contamination of the acid with metallic salts which may precipitate and form a bothersome solid phase, large changes in the composition of the fuming nitric acid, and development of excessive pressures within certain ranges of composition. In fuming nitric acid, the corrosion processes, if not inhibited by passivating coatings on the metal, go to completion according to the equation

$$M + 2n\mathrm{HNO_3} \rightarrow n\mathrm{NO_2} + n\mathrm{H_2O} + M(\mathrm{NO_3})_n \quad [1]$$

where M represents a metal whose valence in the oxidized state is n.

The thermal decomposition of HNO_3 can give rise to excessive storage pressures and changes in acid composition within ranges of initial composition low in NO_2 and H_2O according to the following chemical equilibrium (11–16)

$$2\mathrm{HNO_3} \leftrightarrows 2\mathrm{NO_2} + \mathrm{H_2O} + {}^1/_2\,\mathrm{O_2} \quad [2]$$

Thus, excessive storage pressures in pure HNO_3 arise because of the formation of O_2, which is fairly insoluble in the liquid phase (17). NO_2 and H_2O compared with O_2 are relatively soluble in HNO_3; therefore, the gas phase contains mainly O_2 from the thermal decomposition of HNO_3. During the storage period, if both corrosion and thermal decomposition occur, the composition of the acid changes continuously; thus, the undesirable feature arises of having only an acid of variable composition available during this time for use as a rocket propellant.

It has been found that, by the addition[5] of HF as an inhibitor to fuming nitric acid, the corrosive attack on certain aluminum and stainless steel alloys can be reduced. The addition of suitable quantities of both NO_2 and H_2O to the fuming nitric acid can minimize the amount of O_2 formed and thereby reduce the magnitude of storage pressures at equilibrium, as is evident from the mass-action principle applied to Equation [2]. Shown in Fig. 1 is the effect of NO_2 and H_2O in reducing pressure at chemical equilibrium for acid containing 0.5 wt per cent HF. Other considerations of importance in determining the optimum amounts of NO_2 and H_2O and of HF as a corrosion inhibitor in the fuming nitric acid are:

1 Minimum quantities of H_2O and HF should be added consistent with low maximum storage pressures and low rates of corrosion, since these additives are diluents as far as oxidizing power of the propellant is concerned.

2 An optimum amount of NO_2 is that which gives at chemical equilibrium a low O_2 pressure and yet does not give excessive NO_2 vapor pressure for handling and transferring the fuming nitric acid under atmospheric conditions. As seen in Fig. 2, the vapor pressure of fuming nitric acid markedly increases with increase in NO_2.

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[1] This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract DA-04-495-Ord 18, sponsored by the Department of the Army, Ordnance Corps.

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[3] Since even traces of NO_2 impart a red color to nitric acid, the term "fuming nitric acid" instead of the more indefinite terms based on color, "red fuming nitric acid" and "white fuming nitric acid," is used frequently throughout this paper to represent the ternary system HNO_3–NO_2–H_2O for all compositions greater than about 70 wt per cent HNO_3 and less than 5 wt per cent H_2O. In this composition range, vapor from the system fumes; thus, the term "fuming nitric acid" is physically descriptive. Composition is expressed throughout on a formal weight per cent basis unless otherwise designated. The term "NO_2" is used to designate equilibrium mixtures of NO_2-N_2O_4.

[4] Numbers in parentheses indicate References at end of paper.

[5] The investigation of hydrofluoric acid as a corrosion inhibitor for metals was prompted by a report from the Naval Air Rocket Test Station and at about the same time from North American Aviation, Inc., that the corrosion of stainless steel (SS) 347 by fuming nitric acid was inhibited by trace quantities of HF in the fuming nitric acid.

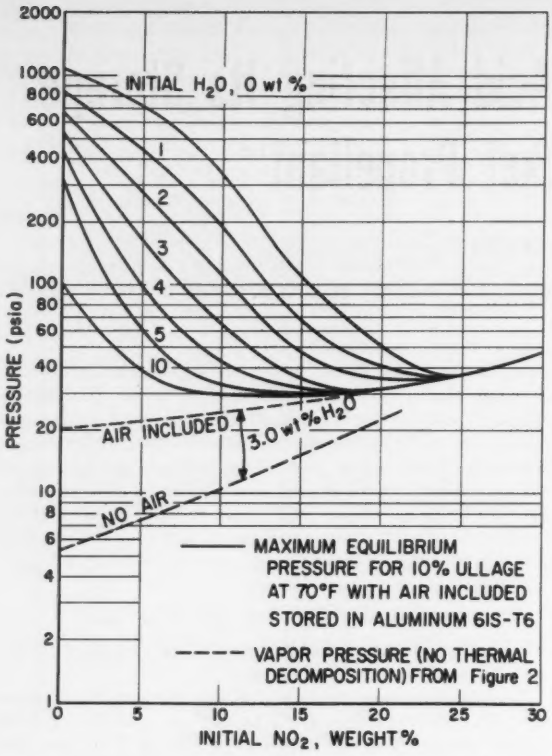

Fig. 1 Pressure at chemical equilibrium of HNO_3-NO_2-H_2O system at 130 F

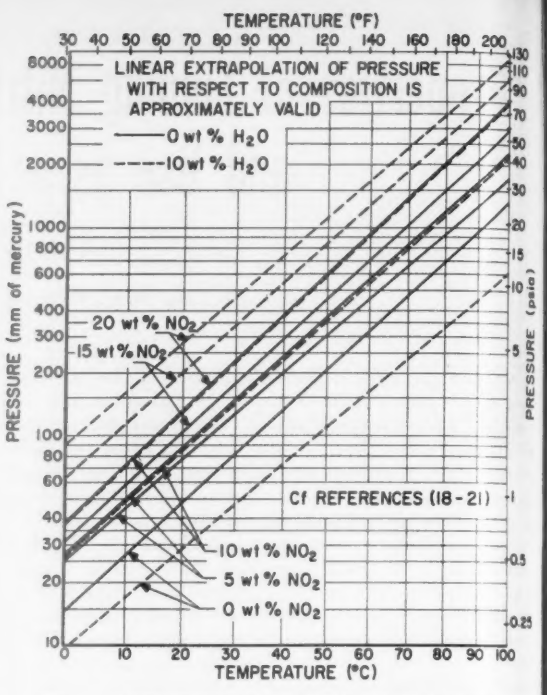
TEMPERATURE (°F)
LINEAR EXTRAPOLATION OF PRESSURE WITH RESPECT TO COMPOSITION IS APPROXIMATELY VALID
0 wt % H_2O
10 wt % H_2O
20 wt % NO_2
15 wt % NO_2
10 wt % NO_2
5 wt % NO_2
0 wt % NO_2
Cf REFERENCES (18-21)
PRESSURE (mm of mercury)
PRESSURE (psia)
TEMPERATURE (°C)

Fig. 2 Vapor pressure of the HNO_3-NO_2-H_2O system

3 The composition of the fuming nitric acid must be such as to give other physicochemical properties desired in a propellant, e.g., a low freezing point and high specific gravity.

The kinetics of combustion and therefore the stability and efficiency of combustion in rocket motors can, with some fuels, be markedly affected by the composition of fuming nitric acid. In the present paper only the optimum composition of acid from the point of view of good storability and the above criteria is considered and not the effect of composition on combustion performance.

Corrosion of Metals

Studies of corrosion of aluminum alloys and stainless steel alloys of the 18-8 per cent Cr-Ni class by fuming nitric acid have shown in general an inhibiting action of both liquid and gas phase corrosion by 0.4 to 0.6 wt per cent HF. These metals are thus recommended for use with HF-inhibited fuming nitric acid. Shown in Figs. 3–5 is a summary of corrosion data on several types of metals. In some cases, even mild steel has shown inhibition by HF, but with decreasing alloy content the passivation becomes more marginal. A more detailed discussion of corrosion is given elsewhere (9, 10). With inhibition of corrosion of metals, one major problem of storage of fuming nitric acid is solved.

Pressure at Chemical Equilibrium and Vapor Pressure

The rate of thermal decomposition of fuming nitric acid at elevated temperatures (130 F) is generally high enough to attain equilibrium and maximum storage pressures within storage periods of about 1 month (1 and 16). Excessive maximum storage pressures occur in samples of fuming nitric acid lean in NO_2 and H_2O (11–15). In Fig. 1 is shown a summary of maximum storage pressure as a function of composition for fuming nitric acid with 0.5 wt per cent HF stored at 130 F in aluminum 61S-T6 vessels and 10 per cent ullage[6] as measured at 70 F. It is seen that samples of fuming nitric acid containing approximately 12 to 16 per cent NO_2, 2 to $3^1/_2$ per cent H_2O, and 0.5 per cent HF give average maximum pressures not exceeding 75 psia at 130 F. For fuming nitric acid within this composition range, HNO_3 is decomposed to an extent of only about 0.5 per cent at the end of the storage period.

When the percentage of NO_2 is more than about 16 per cent for fuming nitric acid containing 3 wt per cent H_2O, the vapor pressure of the system at 130 F is above atmospheric, as seen in Fig. 1, thus causing excessive fuming during handling. Therefore, about 16 per cent represents the maximum optimum NO_2 content from the point of view of both minimum chemical equilibrium pressure and vapor pressure. With increasing H_2O content, the pressure is reduced; but it is desirable to keep the amount of H_2O as low as practicable, since this species reduces the oxidizing power of the acid. Vapor pressure data over a wide range of conditions are shown in Fig. 2 (18–21).

For comparison with the fuming nitric acid just described, pure HNO_3 with 0.5 per cent HF gives a maximum storage pressure of 1100 psia at 130 F and 10 per cent ullage when stored in A1 61S-T6. The HNO_3 decomposes to an extent of about 19 per cent during storage. The high pressure of fuming nitric acid initially lean in NO_2 and H_2O precludes its practical storage in lightweight drums. Also, as a result of corrosion and decomposition, the final fuming nitric acid contains about 9 per cent NO_2 and 1 to 2 per cent H_2O; thus during storage, an oxidant of constant composition is not available for use. If the vessel is vented during storage to avoid excessive pressures, toxic fumes are distilled off, and even more extensive thermal decomposition results. It thus appears that fuming nitric acid of composition in the range 12 to 14 per cent NO_2, 2 to 3.5 per cent H_2O, and 0.4 to 0.6 per cent HF is thermally stable, has a low vapor pressure,

[6] The term "ullage" refers to the relative volume of the gas phase expressed in percentage of the combined volume of the liquid and gas phases.

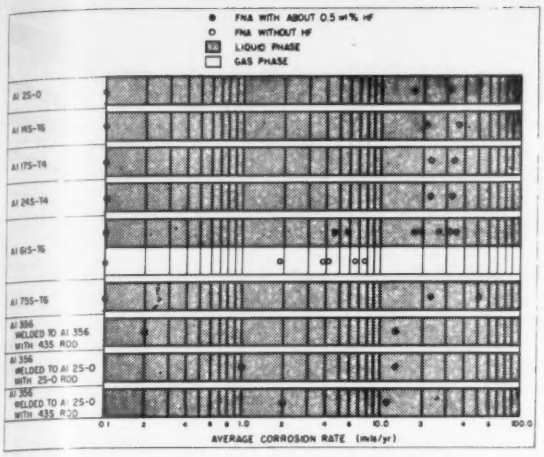

Fig. 3 Summary of data on corrosion of aluminum alloys by fuming nitric acid containing 14 weight per cent NO_2; 3 weight per cent H_2O with and without HF

is noncorrosive toward certain steel and aluminum alloys, and, as will be discussed subsequently, has other physical properties leading to its general use as a rocket propellant.

Miscellaneous Physicochemical Properties

Physicochemical properties, such as density and viscosity, and thermal properties, such as heat capacity and thermal conductivity, are of interest in the handling of fuming nitric acid, particularly in flowing systems where processes of heat transfer and fluid friction are involved. Melting points are of interest in connection with storage at low temperatures around −60 F where it is necessary to avoid the formation of solid phase material.

Densities and Viscosities

Densities and viscosities are available for compositions in the range 75 to 100 wt per cent HNO_3, 0 to 20 wt per cent NO_2, and 0 to 5 wt per cent H_2O, from 32 to 104 F (22). Similar data in composition range of 94 wt per cent HNO_3 or greater are given in the literature (23). In this range of composition and temperature, the absolute viscosity varies between approximately 0.6 and 2.9 centipoises, and the density varies between approximately 1.46 and 1.62 gm/cc. The viscosity of HNO_3 solutions increases with an increase in NO_2 or H_2O and the density increases with an increase in NO_2 and decreases with an increase in H_2O. For best rocket loading density, it is essential to have as much NO_2 in the system consistent with reasonably low vapor pressure. In Fig. 6, effect of composition on the kinematic viscosity and density at 32 F are shown.

Thermal Properties

Values for the thermal conductivity and heat capacity of fuming nitric acid in the range of composition 94 wt per cent HNO_3 or greater are available (23). These data are utilized to calculate recommended values of parameters of importance in heat transfer and fluid friction in flowing systems (24). There is definitely a need for measurements of these properties over a wider range of composition than is now available.

Melting Points

Melting point measurements are available for the binary systems and a portion of the ternary system in the composition range 0 to 25 wt per cent NO_2 and 0 to 18 wt per cent

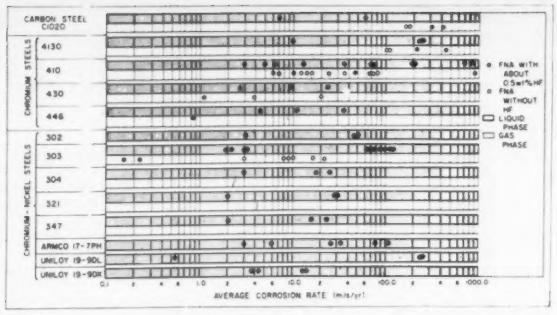

Fig. 4 Summary of data on corrosion of steel alloys by fuming nitric acid containing 14 weight per cent NO_2; 3 weight per cent H_2O with and without HF

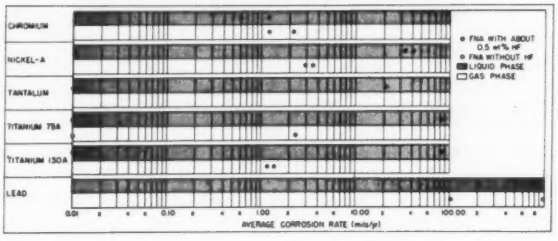

Fig. 5 Summary of data on corrosion of miscellaneous alloys by fuming nitric acid containing 14 weight per cent NO_2; 3 weight per cent H_2O with and without HF

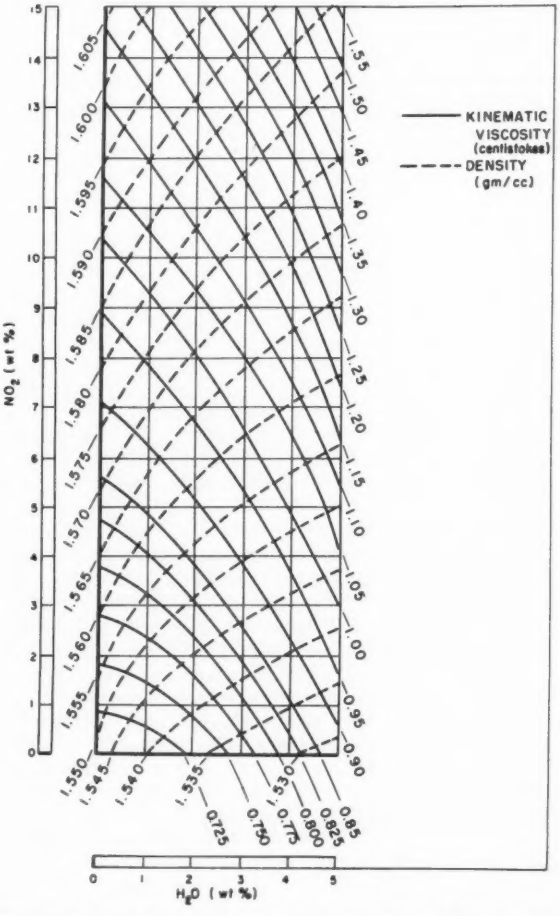

Fig. 6 Curves of constant kinematic viscosity and density for the HNO_3-NO_2-H_2O system at 32 F

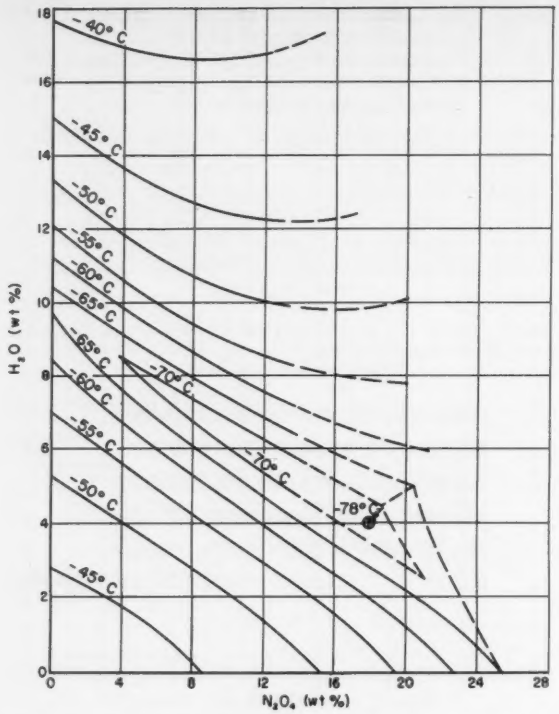

Fig. 7 Curves of constant melting point for the HNO_3-NO_2-H_2O system

H_2O (25). Smoothed data are shown in Fig. 7. It is evident from these data that fuming nitric acid in the composition range 12 to 16 wt per cent NO_2 and 2 to 3.5 per cent H_2O has a freezing point ranging from about −62 to −87 F, which is sufficiently low for storage in cold climates.

Methods of Chemical Analysis

A good review of wet methods of analysis, as well as of instrumental methods of analysis, is given in the literature (26). One difficulty encountered with wet methods of analysis is that the water is determined by difference, thus imposing large uncertainty on this quantity. An instrumental method for the specific determination of water has been developed utilizing the strong optical absorbance of water in the infrared region (27). An electrical conductometric method has been developed for analysis of the ternary system requiring no gravimetric or volumetric measurements (28).

Most methods presently available for complete chemical analysis of the system are too tedious for use in the field. For field use, it seems most practical to use a simple test procedure that indicates whether or not the system is within limits of composition. At the onset of storage, the composition of the system can be obtained at a laboratory. The composition range allowable at the onset of storage (at time of procurement) must be narrower than the composition range allowable for use. Then a test showing a departure from the initial composition can be used. Such a test might involve the use of some easily measured physical properties such as electrical conductance and temperature, and if the conductance were found to lie within an allowable band, the sample would be acceptable. In Fig. 8, as a function of temperature, conductance data are available for fuming nitric acid in the allowable range for use of 12 to 16 per cent NO_2, 2 to 3.5 per cent H_2O, and 0.5 per cent HF. A simplified conductometric method of testing is described elsewhere (29). However, with fuming nitric acid of composition that gives good stor-

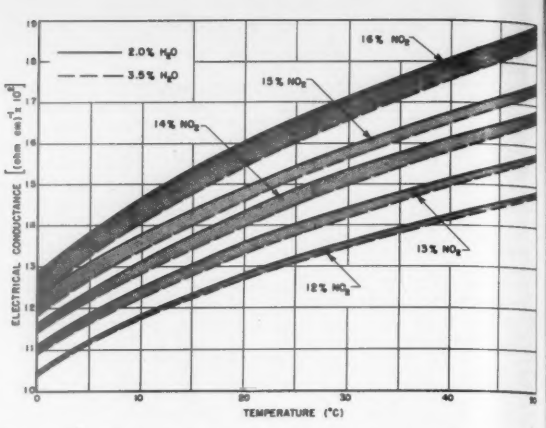

Fig. 8 Conductance of fuming nitric acid acceptable for use as a function of temperature

ability from the point of view of both thermal stability and corrosion, very small changes of composition should be encountered during storage in closed drums. Thus, the drum should be opened for tests as infrequently as possible to minimize losses of volatile constituents.

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(*Continued on page 756*)

Medical Problems Involved in Orbital Space Flight

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After analyzing the various kinds of space operations that might be expected in the near or remote future (space equivalent flight, circumplanetary space flight, and interplanetary space travel), the second phase—circumplanetary space flight or orbital space flight—is chosen as a platform for the discussion of some of the most important medical problems involved in space operations. First, the state of weightlessness is discussed with regard to its effect upon the general well-being of the occupants of a satellite vehicle and in regard to its sensomotor effects. In connection herewith, the optical situation is considered with regard to the properties of the environment and the visual appearance of the light sources. Furthermore, physiological day-night cycling is discussed in an environment where there is no natural day and night. And finally some problems involved in human engineering of the space cabin concerning pressurization, supply of oxygen and removal of carbon dioxide, photosynthetic gas exchange, and the event of sudden decompression of the cabin are discussed. Some of these problems are presently under study in an experimental space cabin simulator.

Introduction

FOR about seven years space medicine—a branch of aviation medicine—has been studying the human factors involved in flights into the upper atmosphere and beyond, into space. There are various phases of this kind of flight depending upon the physical and physiological characteristics of the environment, the speed of the vehicle, and upon the destination of the flight.

The first phase of space operations that we can expect in the immediate future will be the long distance flights at supersonic and hypersonic speeds through the space equivalent regions of the higher and upper atmosphere. These flights will be the logical development of the present-day long distance atmospheric flights on a global scale and can justly be called global or long distance space equivalent flights. With regard to motion dynamics, part of the time the vehicle exhibits airplane status and part of the time projectile status. We are now at the threshold of this first phase of space flight, namely, global space equivalent flight (10, 27).[2]

The second phase in the development of human space flight will have been achieved as soon as the orbital velocity of about 17,500 mph has been reached. This speed, which enables a vehicle to circle for a longer period of time or even permanently around the earth in an orbit, gives the vehicle satellite status. This is circumplanetary space flight or, more specifically, circumterrestrial space flight (4).

As soon as the escape velocity of 25,000 mph has been reached, the vehicle will have attained spaceship status; this will be the final phase of space flight and can truly be called interplanetary space travel (34).

It is my purpose in this paper to discuss the medical problems involved in the second phase of space operations, namely, that of circumplanetary space flight or satellite flight. This is full-fledged space flight in its simplest form: full-fledged, because all of the strange environmental and motion conditions associated with space flight are encountered; in its simplest form, because the vehicle's movement is uniform with regard to speed and trajectory. Circumplanetary space flight, therefore, is an especially suitable example for discussion of the fundamental medical problems confronted in space flight. As for its technical side, see (4, 9, 11, 21, 24, 25, 26, 31, and 34).

The first step in the direction of this phase of space flight is the instrumented unmanned satellite, such as the one to be launched in 1957 (18); but we shall take a step further and assume, for the purpose of our discussion, an instrumented manned satellite. We shall not, however, discuss how this vehicle arrives at its orbit and the medical (acceleration) problems involved—which are not insurmountable—but rather we shall presume to be at the stage where the vehicle has already reached a certain orbit and has attained satellite status. But, I should like to add at this point, this paper in no way directly relates to the scientific satellite program which is presently under way.

The speed required to attain satellite status is about 18,000 mph near sea level. The denser regions of the atmosphere would prohibit this speed because of air resistance and friction heat. At about 120 miles or 200 km, however, the air is without noticeable effect in both respects (5). This aerodynamic and aerothermodynamic border of the atmosphere can therefore be designated by the more general term, flight effective limit or final functional limit of the atmosphere. The actual material border of the atmosphere, however, reaches into the area of 600 miles or 1000 km from where we enter, through a 600-mile-wide spray zone, into interplanetary space. But it must be emphasized that even above the final functional border the atmospheric environment is space equivalent in practically every respect. It is here that the laws of aerodynamics lose their meaning and those of astrodynamics (Romick) become fully effective, rather than at the material limit of the atmosphere.

Above 120 miles, therefore, the nearest satellite orbit is conceivable. The orbital speed required at this level is, roughly, 17,500 mph and the period of revolution is about 88 min. Naturally, with increasing altitude, the orbital velocity decreases and the period of revolution increases.

For our medical discussion, let us assume the 2-hr orbit slightly above 1000 miles, as chosen by W. von Braun for his space platform. At this altitude we are in the exosphere, far beyond the final functional limit and also beyond the material limit of the atmosphere. The particle density is about 10 per cm^3. In the 2-hr orbit the orbital velocity is about 15,800 mph.

Weightlessness

Characteristic of orbital flight is the fact that the gravitational pull of the earth and the centrifugal forces caused by the vehicle's inertia are balanced, which means that the vehicle and its occupants are in the state of weightlessness or zero gravity. This is the first of the medical problems that I would like to discuss. There are two sides to this problem: (a)the general medical aspect regarding the well-being of the occupants, and (b)the sensory physiological aspect concerning perception of position of the body in space and sensomotor control of the movement of the body and its parts.

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[2] Numbers in parentheses indicate References at end of paper.

So far, experiments on man—to study the effect of zero gravity (16)—have been carried out only up to 30 sec in parabolic flight maneuvers in jet planes. The experiments of E. R. Ballinger (2) in Wright Field Aero-Medical Laboratory in 1952, those of Harold von Beckh in Buenos Aires (3) in 1953, and most recently those of S. J. Gerathewohl in Randolph Field, Texas, do not as a rule indicate a general disturbance in the automatic nervous system which controls respiration and circulation. J. P. Henry et al. (17) in their recordings on monkeys in a V-2 and an Aerobee during a 3-min period of zero gravity, found no evidence of a significant disturbance of the cardiovascular or respiratory system. So far, we have no proof that there would be any difference during a longer period of time, such as would be found in a satellite. A possible shift in blood pressure, due to the absence of hydrostatic pressure in the blood vessels, might be easily regulated by the presso-regulators of the arterial system. The whole problem boils down to the question of the possibility of adaptation to the state of zero gravity. Such adaptation seems to be a possibility. At this point, I should like to add that a manned artificial satellite is the only means of bringing about a final solution of this entire problem, because it alone offers the possibility of experiencing the gravity-free state for periods of days, weeks, and months, not too far from the earth.

As to the second, or the sensory aspect of the gravity-free state, this can be said: we have several sense organs, or specific nerve endings, that serve as gravi-receptors, such as the centrally located otolith organ and the receptors of the pressure sense distributed peripherally over the entire skin (about 20 per cm^2); specific nerve endings in the muscles, the so-called muscle spindles; and, finally, specific nerve endings in the connective tissue, the Pacinian corpuscles. They all belong to the category of mechano-receptors; these receptors have an exteroceptive function insofar as they react to external forces and inform us about the outer world. One such external force is the gravitational pull of the earth. They also have an enteroceptive or a proprioceptive function insofar as they inform us about the tension conditions in the skin, the muscles, and the connective tissue. They play, therefore, an important role in the senso-motor control of the movements of the whole body as well as of its parts. In the case of the vestibular apparatus and the presso-receptors of the skin, the exteroceptive function is more pronounced; in the other mechano-receptors, the proprioceptive function is dominant.

In the gravity-free state the exteroceptive or the gravi-receptive function of the mechano-receptors is eliminated; the proprioceptive function, however, is not. For this reason, a man making a high dive from a diving board is able to perform a variety of acrobatic jumps quite skillfully, although he is in a gravity-free state throughout the dive. In a gravity-free state the absent gravi-receptive (exteroceptive) function of the mechano-receptors is substituted by the exteroceptive sensory organ par excellence: the photoreceptors or, in other words, the eyes. When in the gravity-free state, as in a satellite, the eyes will be the only sense organ that informs the occupants of their position in space. This brings us to the problem of vision in space.

Visual Problems

Of what kind are the light sources that confront us in space? Direct sunlight and starlight are first; we are also confronted by indirect sunlight coming from the earth, reflected by the continents, the oceans, and especially by the clouds. Moreover, some of the indirect sunlight is scattered from the denser layers of the atmosphere back into space. Finally, we have indirect sunlight reflected from the moon's surface. But there is no skylight and this is the factor that makes the visual conditions so strange in the regions where satellites are conceivable. Skylight is sunlight scattered in all directions by the air molecules. Because the short wave part of the visible spectrum is especially affected, the scattering produces the diffuse blue daylight in the denser regions of the atmosphere, as it is observed from the earth's surface. Against this rather bright skylight, during the daytime the stars fade into invisibility. With increasing rarefication of the air molecules in higher altitudes, scattering of light diminishes gradually and ceases at about 80 to 100 miles (15). This is the optical functional border between atmosphere and space or the visual space equivalent level within the atmosphere. It is the dividing line between atmospheric optics and space optics. Beyond this level the sky is permanently dark. The extra-atmospheric sky luminance is only 10^{-5} mL as compared with that of 500 mL, the average value in the lower atmosphere. But the sun is visible in its full brilliance against the dark sky, except of course when the satellite moves through the shadow of the earth. The stars are also visible all the time, and when its position allows, the moon can be seen in full brightness together with the sun. Because of the lack of skylight in space, the contrast between light and dark is a dominant feature. Everything that is exposed to sunlight appears in full brightness and vivid color, and everything else is in the darkness of shadow. The extra-atmospheric illumination is around 13,500 ft-c compared with 10,000 ft-c at the earth's surface. Light and shadow dominate the scenery, comparable to the light and shadow effects such as those produced on the stage for the magician. This strange photoscotic condition poses physiological problems in the field of contrast vision and retinal adaptation (7, 15). And the strange distribution of the light sources, sun, stars, and the indirect sunlight from the earth and moon, is of special interest from the standpoint of orientation in space (6).

At this point I should like to make a comparison with an environment that is, so to speak, the extreme opposite of that found in space, namely, the deep sea. But there are also some similarities, according to the well-known proverb, "les extrêmes se touchent."

W. Beebe observed in his "bathysphere" that the light intensity in the sea decreases rapidly with increasing depths. At a depth of 1600 ft, light is completely absent in the Atlantic Ocean. In these regions we find fish with luminous organs and telescopic cylindrical eyes. At depths of about 10.000 ft there are fish with only vestigial eyes. These deep sea fish rely almost entirely on the mechano-sensory system of their skin to sense the environment. This represents an extreme contrast to the situation that will be experienced by man under space conditions. In the darkness of the deep sea, where the photo-receptors are out of function, the position and movement of the fish is controlled solely by the gravi-receptors; in the darkness of deep space and under the gravitational conditions of orbital space flight where the gravi-receptive function of the mechano-receptors is eliminated, orientation of man depends entirely upon the photo-receptors or upon vision.

We do not know whether man can adjust to purely optical orientation in space. Fish can be trained for an optical orientation in their environment. Several years ago it was found by E. von Holst that when an aquarium in a dark room was covered with a black plate and the light penetrated through the glass bottom, some of the fish will swim upside down, and will look for fresh air at the bottom which is lighted and will swim to the dark surface of the water when they want to rest.

In orbital space flight, the sun, the stars, and the earth and moon are the optical footholds for the visual orientation in space. The observation of the sun, however, poses an important medical problem. The brilliant radiance of the sun in its original intensity, while not affected by atmospheric absorption and scattering, represents a hazard to the eyes. A much shorter time of exposure is sufficient to cause a retinal burn, such as that known to the ophthalmologist, as it occurs occasionally when someone observes a solar eclipse through an insufficiently smoked glass. The result of such a so-called "eclipse blindness" is a scotoma or a blind spot in the visual

field. Outside of the atmosphere, the danger of such a retinal injury by direct solar light is much greater, and from an artificial satellite the sun should be observed only through glass with very high absorptive power.

In connection with the optical conditions found in the space equivalent regions of the atmosphere beyond 120 miles and in interplanetary space, I should like to touch upon a physiological problem that has never been discussed in space medical papers. It is the problem of maintenance of an adequate physiological day-night cycle for the occupants of a space vehicle.

Physiological Day-Night Cycling

In orbital space flight, the concept of natural night loses its meaning and must be replaced by that which night really is, namely, the shadow of the earth.

The shadow or umbra of the earth tapers down in the form of a cone 859,000 miles or 1,385,000 km deep into interplanetary space. Travelling through the greatest width of this sunless dark cone would take our assumed satellite about 50 min. During the remaining part of the revolution (about 70 min) the vehicle is exposed to the sun and surrounded by darkness at the same time, as described earlier. Such are the optical conditions if the satellite orbit passes through the earth's shadow.

Many different orbital planes, however, are conceivable; in every case at a distance of about 1000 miles an adequate ambient physical day-night cycle is absent because the day-night or, more precisely, the sunlight-shadow cycle is only 2 hr. Therefore, we must create and maintain an artificial day-night cycle within the satellite to meet the physiological requirements of the occupants. For, adequate diurnal cycling is of great importance to the health and efficiency of man. In fact we are physiologically so strongly adapted or so bound to a day-night cycle, manifested in rest or sleep and wakefulness or activity, that it must be regarded as a biological law. To ignore this law, after a week or so, would lead to a complete nervous breakdown (19, 33).

How can an adequate day-night cycle be achieved for the occupants of an artificial satellite? For them, the night must be induced in a special night compartment or by a device covering the eyes. The question is posed as to the time pattern of such an artificial day-night period.

In this regard, reference is made to the important basic experiments carried out in the Mammoth Cave in Kentucky, 1940, by N. Kleitmann, Professor of Physiology at the University of Chicago (19). Dr. Kleitmann spent two months in this cave with several co-workers, under artificially regulated day-night cycles of different lengths. The result of these experiments showed that man can adapt himself to a diurnal cycle only in the range from 18 to 28 hr. Within this range the temperature curve of the body follows the various cycles. When a cycle shorter than 18 hr or longer than 28 hrs was introduced, no adaptation was possible and the temperature curve returned to its normal cycle of 24 hr.

This gives us the clue for solving the problem of diurnal cycling in a manned satellite. If we choose a minimum day-night cycle of 18 hr, dividing it into 8 hr for sleep, 2 hr for recreation, and 8 hr for duty, that would be a reasonable solution. Or, if a 24-hr day-night cycle is selected, the best plan for a subdivision of this cycle would be 8 hr for sleep, 8 hr for rest and recreation, and 8 hr for duty. This presupposes that the crew will be large enough to be subdivided into three groups. In the case of an artificial 18- or 20-hr day-night cycle, a two-group crew would be sufficient for a manned satellite operation.

Human Engineering of Space Cabin

We may assume that the metabolic rate of an occupant of an artificial satellite during his duty hours, is about the same as that of an individual on earth during moderate work; the total metabolism during a 24-hr period, including sleep and recreation, would then be on the order of 2500 cal for a 70-kg man. This brings us to the respiratory requirements for the satellite crew or, more generally speaking, to the climatization of the cabin (1, 13, 22, 7). The cabin in a satellite must, of course, be completely closed—a sealed cabin in which an adequate atmosphere is artificially created and controlled. It must be emphasized, however, that such a type of cabin is required even down to the atmospheric region of 70,000 to 80,000 ft.

One of the vital tasks in the climatization of the sealed cabin is the solution of the oxygen problem for respiration.

From the afore-mentioned metabolic rate of 2500 cal per man per day, we can calculate the amount of oxygen required by one man per day. The thermal equivalent of 1 l of oxygen is 4.85 cal under normal nutritional conditions. This means that the biological production of 1 cal requires 206 cm^3 of oxygen. Consequently, the total amount of oxygen consumed per man per 24 hr is roughly 500 l or 0.7 kg. This amounts to 58 kg of oxygen per man for 1000 satellite revolutions that take place in 83 days in our assumed orbit at the 1000-mile altitude, or 348 kg O_2 for a crew of six. Replacement of the consumed oxygen from the storage tanks must be controlled in such a way that the oxygen pressure does not fall below 100 mm Hg. This is about the minimum permissible limit for comfort and efficiency; it should not surpass the permissible maximum of about 350 mm Hg because O_2 concentrations above this level are toxic (8). This shows that we can tolerate a rather wide variation in oxygen pressure (from 100 to 350 mm Hg), which facilitates considerably the oxygen problem in space flight.

Whereas oxygen is consumed in the metabolic processes of the body cells, carbon dioxide is produced in the same process and exhaled. Under normal nutritional conditions, the ratio between exhaled carbon dioxide and consumed oxygen, the so-called respiratory quotient, is 0.85. In our example, one man produces 425 l of carbon dioxide or 0.837 kg per day or 70 kg per 1000 satellite revolutions. This would be 420 kg for a crew of six. Carbon dioxide in concentrations above 3 vol per cent is toxic; the permissible limit for a longer period of time lies at about 1 vol per cent under standard barometric pressure and temperature conditions, or at about 8 mm Hg. The removal of the excess carbon dioxide in the sealed cabin vehicle, which can be achieved by certain chemicals or in a physical way is, therefore, just as vital as the maintenance of an adequate oxygen pressure.

Since the consumed oxygen appears again in bound form, namely, within the carbon dioxide of the expired air, it has been suggested to try to regain the oxygen from the carbon dioxide, in this way eliminating a toxic gas and at the same time facilitating the problem of oxygen supply.

A natural method accomplishing this is known to us in the process of photosynthesis, found in chlorophyl-bearing plants. Photosynthesis is the reverse process of respiration as a comparison of their reaction formulas shows

$$\text{Respiration:}\quad C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$$

$$\text{Photosynthesis:}\quad 6CO_2 + 6H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + O_2$$

In respiration or biological oxidation, oxygen is consumed and carbon dioxide and water are produced. This process requires several so-called respiratory enzymes. In photosynthesis, oxygen is produced and carbon dioxide and water are consumed. This process requires the presence of chlorophyl as an enzyme.

In special studies sponsored by the U.S.A.F. School of Aviation Medicine, it has been found by J. Myers, head of the Department of Algal Physiology, University of Texas, Austin (23), that 2.3 kg fresh weight of a certain alga—the alga chlorella pyrenoidosa—with regard to gas metabolism, under optimal conditions, is sufficient to support one man. This means that this mass of algae consumes as much carbon

dioxide and produces as much oxygen per time unit as one man produces carbon dioxide and consumes oxygen during the same period of time. Both, therefore, could live together and support each other with regard to the respective respiratory and photosynthetic requirements in a symbiotic-like relationship in a closed system for a considerable length of time.

Plants like the alga chlorella are especially suitable as photosynthetic gas exchangers. They are small round bodies about the size of red blood cells and are dispersed in a nutritional solution. These primitive plants are perfect photosynthetic machines, since they have no specific organs nor various functions like the higher plants. Their only function is to build up carbohydrates and to produce oxygen photosynthetically. Primitive plants of this type appeared on this planet $1^1/_2$ billion years ago. And they might have been responsible for an early buildup of an initial stock of oxygen in the primitive atmosphere or proto-atmosphere of the natural satellite of the sun, namely, the earth. But the difficulties in the use of such photosynthetic gas exchangers lie in the volume and weight of the device, in the arrangement of and in the power requirement for illumination. As for the latter, solar energy may be the answer. For flights of short duration, however, we certainly shall never resort to a biological gas exchanger. For flights over weeks and months it might be different. Perhaps some day we shall have a type of photosynthesis that can utilize infrared; or the efforts that have been made for a number of years in order to achieve artificial photosynthesis may one day be successful.

In the sealed cabin also, the water vapor given off—in amounts of from 50 to 80 gram per man per hour through respiration and perspiration under comfortable temperature conditions by the occupants—must be kept within the comfort limits that range between 30 and 50 per cent relative humidity. And, finally, the barometric pressure should be kept at levels corresponding to that found near sea level and up to 9000 ft. In this respect, however, the physiologist could make concessions to the engineer, who for structural reasons would probably desire a lower pressure differential between the cabin's air and the surrounding near vacuum. From the physiological point of view, a minimal barometric pressure corresponding to an altitude of about 15,000 ft would be acceptable.

The multitude of factors involved in the climatization of the sealed cabin requires a complex instrumentation for automatic control. The School of Aviation Medicine, U.S.A.F., Randolph Air Force Base, Texas, now has an experimental sealed chamber (Fig. 1) in which we can study the changes of the atmospheric conditions caused by the presence of the occupants, and the means to control these factors. This space cabin simulator can also serve as an indoctrination chamber in handling the situation in case the automatic controls fail or the cabin develops a leak.

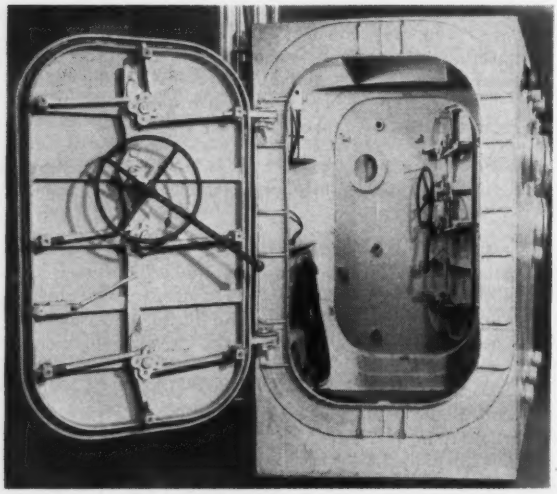

Fig. 1 The space cabin simulator of the School of Aviation Medicine, U.S.A.F., Randolph Air Force Base, Texas

Decompression Event of the Space Cabin

With this point we touch upon the Achilles' heel of the sealed cabin vehicle. One of the causes of a leak might be a collison with a meteor (20), a probability which is very remote; however, the occupants of a satellite vehicle must be prepared for such an event, even though meteor bumpers or screens—suggested by F. Whipple (35) and others—might offer effective protection.

In the lower atmosphere, the time rate of decompression of the pressurized cabin is governed by four factors: the volume of the cabin, the size of the hole, the barometric pressure within the cabin, and the barometric pressure of the ambient atmosphere. In a satellite vehicle, the last factor is practically zero, which means that under other equal conditions the decompression will be faster and more violent. In any event, the crew must know that a drop in oxygen pressure to 100 mm Hg will affect their efficiency, as mentioned earlier, and at an oxygen pressure of 60 mm Hg the situation will become critical and dangerous. Before this critical level is reached, the source of the leak must be sealed; otherwise, the crew would face the whole physiological sequence of decreasing air pressure effects.

Conclusion

These are some of the medical problems encountered in orbital space flight. I have not touched upon the radiation and temperature problem (12, 28, 29, 30) which has been discussed in the paper of David G. Simons (30).

All of the space medical problems discussed so far are also encountered in transfer orbits to other celestial bodies, that is, in interplanetary space travel. Some of them will be faced also, more or less, during a certain portion of space equivalent flights, that is, in long distance flights at hypersonic speed through the space equivalent regions of the atmosphere, as previously defined. But we find them, so to speak, in classical form in nearly circular orbital space flight.

I have chosen, therefore, this phase of space operations for this paper because it offers an ideal platform for the discussion of the problems of space medicine in general, and provides an up-to-date picture of some of the progress made in this fascinating branch of aviation medicine.

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(Continued on page 756)

Low Pressure Performance of Cylindrical Can Burners

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A study was made of the combustion stability and combustion efficiency of cylindrical can burners, 2 to 5 in. diam, at low pressure (1/6 to 1/2 atm abs). Cans with one, two, and three stages of inlet holes were tested and stability was found to depend primarily on the geometry of the upstream (first) stage of holes and the region inside the can (the recirculation zone) upstream of that stage. Size and location of downstream stages were of minor importance to stability but did affect over-all efficiency. Tests were conducted to determine the effects of varying the number and size of first-stage inlet openings, and the diameter and length of the recirculation zone. The effects of changing pressure, mass flow, inlet jet direction, recirculation zone wall temperature, and tailpipe length were also studied. In an empirical stability correlation, the lean and rich blowout limits are functions of the superficial first-stage velocity divided by the product of can diameter and pressure to the 0.8 power. A can stability mechanism depending on over-all reaction rates in a local zone is suggested.

Introduction

THE can is a type of burner that has proved useful in both ramjet and turbojet combustors. A can burner (see Figs. 1 and 2) is a volume enclosed by solid surfaces on all but the downstream side through which products of combustion exhaust. Holes in the bounding surfaces admit unburned air—or air and fuel—to the burning gases within the can. Fuel may be injected into the air stream either directly inside the can (the usual practice in turbojet combustors) or upstream of the can (the usual practice in ramjet combustors). In these tests, upstream fuel injection was used exclusively; enough fuel-air mixing time was allowed to make the mixture entering the can always completely homogeneous.

The object of this study was to determine the effects on low pressure (1/6 to 1/2 atm abs) performance of changes in can geometry and operating conditions. Two measures of performance used here are combustion stability and combustion efficiency. Stability refers to the range of equivalence ratios (fuel/air ratio divided by the stoichiometric fuel/air ratio) over which a flame can be maintained in the can when all other variables are held constant. Efficiency refers to the fractions of fuel and oxygen that have been chemically consumed at the burner exhaust plane.

Equipment Description and Operation

The particular cans tested here consisted of right circular cylinders 2, 3, and 5 in. nominal diam. (Cross-sections other than circular—annular or rectangular, for example—are also practicable). Most of these cans had a single stage, although some multiple-stage burners were tested. (A stage, or row, is defined as a series of openings with centers in a single plane normal to the can axis, through which air-fuel mixture enters the burner.) The stage farthest upstream is termed the first stage, and other stages are numbered successively.

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[3] Numbers in parentheses indicate References at end of paper.

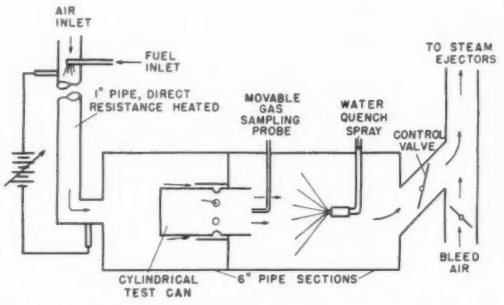


Fig. 1 Schematic diagram of apparatus; arrows denote direction of gas flow

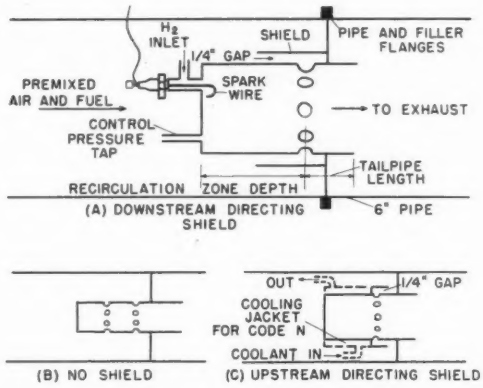


Fig. 2 Cylindrical can configurations for three types of unburned stream entry (details in Table 2)

The burners were tested in the apparatus sketched in Fig. 1. Fuel and air were metered separately, heated and mixed to homogeneity, and led to a pipe section in which the test can was mounted on a filler flange. All of the mixture passed through the one or more stages of holes—none was by-passed. A water spray quenched the combustion products which exhausted to a steam ejector. Pressure was controlled both by bleeding air to the system and by a throttle; the control point was taken just inside the upstream end of the can (see Fig. 2A). Unless otherwise noted, the control pressure was 1/3 atm abs for all tests; the fuel was No. 1 solvent naphtha, a volatile gasoline-like product with typical properties listed in (1).[3] Inlet mixture temperatures averaged 200 F and were not varied systematically; 50 per cent of the runs were at temperatures within 5 degrees of 200 F and 90 per cent within 40 degrees of 200 F.

The flame was ignited by the spark and hydrogen supply shown in Fig. 2A. These were both turned off once ignition occurred. To determine stability limits, fuel rate was changed slowly at constant air rate and pressure until flame blowout occurred. One or two replicates were made immediately to check the results.

All combustion efficiencies were measured while burning stoichiometric mixtures of air and fuel. These efficiencies were determined at the plane of the tailpipe exit; in this

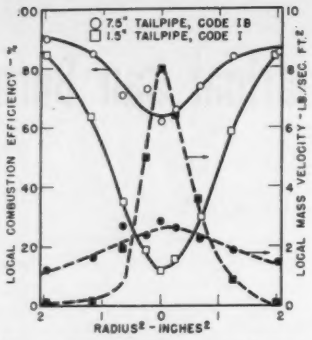


Fig. 3 Typical efficiency and mass velocity profiles at the exit of 3-in. single-stage cans; reference velocity, 89 ft/sec

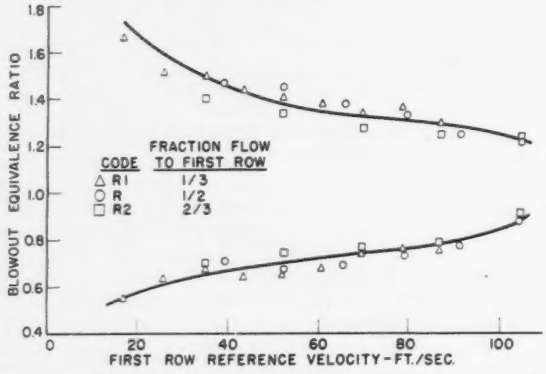


Fig. 4 Control of stability by recirculation zone loading in two-stage 2-in. cans

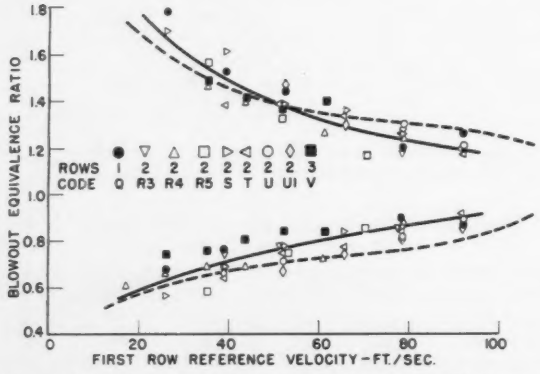


Fig. 5 Control of stability by recirculation zone loading in one-, two-, and three-stage 2-in. cans

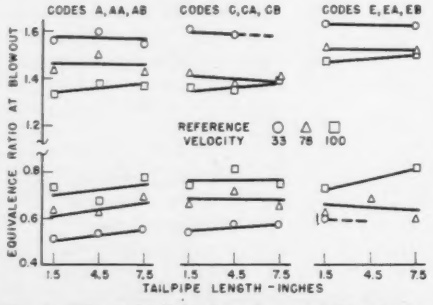


Fig. 6 Effect of tailpipe length on stability of 3-in. cans

plane a movable proble (or rake) was used to measure local total pressure and to remove a local gas sample for oxygen analysis. The efficiencies reported are averages weighted by local mass velocities. Local mass velocities were computed by assuming local temperatures (and densities) to be those corresponding to adiabatic local burning to the observed oxygen efficiency. In most cases the tailpipes were deliberately made short so that efficiencies would be low and differences easily detectable. Typical profiles are shown in Fig. 3. With longer tailpipes, the over-all efficiency level increases and both efficiency and mass velocity profiles become less peaked.

Some of the differences in can geometry are shown in the three parts of Fig. 2. Note that one particular difference is the way in which the stream approaching the inlet holes is directed by the shield (if present). Table 2 lists the detailed dimensions of the 46 different geometries used in these tests; for each geometry, the appropriate part of Fig. 2 is noted in the last column. An average of about six runs was made for each geometry. In most cases a run consisted of measurement of combustion efficiency and rich and lean blowout limits for given air flow and pressure.

Results

Recirculation Zone Control

That part of the can including the first stage of holes and everything upstream of the first stage is termed the recirculation zone. This name derives from the flow pattern in that region. Jets of inlet gases from the first stage impinge at the can axis. After impingement, most of the unburned mixture flows downstream but some of it is directed upstream into the recirculation zone. This fresh mixture enters the burning gases and is itself ignited, burns, and is eventually exhausted from the zone. The recirculation pattern in an ideal system is simple and has been sketched by Clarke (2). In most systems, there are usually large deviations from the nicely symmetric flow assumed by Clarke but the essential patterns are unchanged.

In the tests that follow, particular attention has been paid to the recirculation zone geometry rather than to that part of the can downstream of this zone. This is justified by the results below which show that the performance, particularly the stability, of an entire multistage can is usually controlled by the geometry and loading of the recirculation zone. For example, three two-stage 2-in. cans were tested with the results shown in Fig. 4. These cans differed only in the relative hole areas of first and second stages and thus in the fraction of total flow allowed to enter the first stage. Stability of these cans correlated well by plotting the limits against the reference velocity of the first-stage flow. (The flow entering each stage was assumed proportional to the area of that stage's holes. Reference velocity is the volumetric rate of incoming flow, with density measured at the inlet temperature and control pressure, divided by the can's internal cross-sectional area.) For a given first-stage reference velocity, the total flow increased by a factor of two from can R2 to can R1.

Similar results were obtained with a group of nine other 2-in. cans varying in hole size, tailpipe length, stage spacing, and number of stages. The data in Fig. 5 show a good deal of scatter, but the dominant influence of the first-stage loading is clear. (The solid line in Fig. 5 is an average curve for the points shown; the dotted line is the curve from Fig. 4.)

Stability thus is not much affected by subsequent stages in multistage cans; furthermore, in single-stage cans there is little effect on stability of tailpipe length. Fig. 6 shows blowout data for three tailpipe lengths for each of three recirculation zone configurations (varying greatly in hole size and thus in inlet pressure drop). Except for the Code A series lean limit data, no consistent trends appear as tailpipe length changes.

Table 1 Pressures and equivalence ratios at blowout

Can diam	NGTE Lean ϕ	NGTE Rich ϕ	NGTE P	Esso Lean ϕ	Esso Rich ϕ	Esso P
2.0	0.48–0.73	1.3–2.2	10–30	0.63–1.0	1.0–1.8	10
2.5	0.48–0.66	1.4–2.3	10–30	....	...	..
3.0	0.40–0.65	1.4–2.0	10–20	0.39–1.0	1.0–1.8	5–15
5.0	.....	...	..	0.68–1.0	1.0–1.6	10

Table 2 Details of can geometry

Code	Nominal can diam[1]	Axial spacing[2]	No. of holes	Size of holes[3]	Fig. 2, part
A	3	3, 1.5	8	0.50 × 0.14	(A)
AA	3	3, 4.5	8	0.50 × 0.14	(A)
AB	3	3, 7.5	8	0.50 × 0.14	(A)
B	3	3, 1.5	8	0.50 × 0.25	(A)
C	3	3, 1.5	8	0.50 × 0.42	(A)
CA	3	3, 4.5	8	0.50 × 0.42	(A)
CB	3	3, 7.5	8	0.50 × 0.42	(A)
D	3	3, 1.5	8	0.50 × 0.64	(A)
E	3	3, 1.5	8	0.50 × 1.10	(A)
EA	3	3, 4.5	8	0.50 × 1.10	(A)
EB	3	3, 7.5	8	0.50 × 1.10	(A)
F	3	3, 1.5	3	0.42 × 1.24	(A)
G	3	3, 1.5	3	0.82	(A)
H	3	3, 1.5	5	0.63	(A)
I	3	3, 1.5	8	0.50	(A)
J	3	3, 1.5	16	0.35	(A)
K	3	3, 1.5	30	0.26	(A)
L	3	3, 1.5	3	2.95 × 0.18	(A)
IB	3	3, 7.5	8	0.50	(A)
Ia	3	6, 1.5	8	0.50	(A)
Ib	3	4.5, 1.5	8	0.50	(A)
Ic	3	2.25, 1.5	8	0.50	(A)
Id	3	1.5, 1.5	8	0.50	(A)
5Ia	5	10, 2.5	8	0.83	(B)
5Ib	5	7.5, 2.5	8	0.83	(B)
5I	5	5, 2.5	8	0.83	(B)
5Ic	5	3.75, 2.5	8	0.83	(B)
5Id	5	2.5, 2.5	8	0.83	(B)
5I2	5	5, 2.5	8	0.83 × 1.66[4]	(B)
M	3	3, 1.5	4	0.50	(C)
M1	3	3, 1.5	8	0.50	(C)
N	3	3, 1.5	8	0.50	(C)[5]
P	3	3, 1.5	8	0.50	(B)
Pa	3	1.5, 1.5	8	0.50	(B)
Q	2	2, 3	7	0.40	(B)
R	2	2, 3, 3	7, 7[6]	0.40, 0.40[6]	(A)
R1	2	2, 3, 3	7, 7	0.28, 0.40	(A)
R2	2	2, 3, 3	7, 7	0.40, 0.28	(A)
R3	2	2, 3, 3	7, 7[7]	0.40, 0.40	(B)
R4	2	2, 3, 3	7, 7	0.28, 0.40[8]	(B)
R5	2	2, 3, 3	7, 7	0.40, 0.28[8]	(B)
S	2	2, 1, 2	7, 7	0.40, 0.40	(B)
T	2	2, 2, 1	7, 7	0.40, 0.40	(B)
U	2	2, 2, 1	7, 7	0.40, 0.40	(B)
U1	2	2, 2, 1	7, 7[7]	0.40, 0.40	(B)
V	2	2, 1, 1, 1	7, 7, 7	0.40, 0.40, 0.40	(B)

NOTE:
All dimensions in inches. Unless noted, holes in line (at same angular positions) for multistage cans. All holes equally spaced around circumference. Outer duct is 6″ pipe for all can sizes.

[1] Actual inside diameters of cans 1/8″ less than nominal diameters.

[2] First number is recirculation zone depth; last number is tailpipe length; middle number(s), if any, is distance between stages for multistage cans.

[3] Holes round of diameter tabulated; two dimensions indicate rectangular slots with first dimension giving circumferential opening and second giving axial opening.

[4] Slot with rounded ends (from two 0.83″ holes).

[5] Recirculation zone wall cooled (dotted section added).

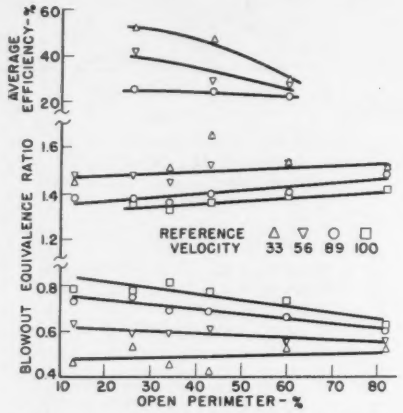
[6] Two stages of holes for each configuration; diameters of first stage given by first number and of second stage by second number. Tailpipe length measured from downstream stage.

[7] Second stage of holes staggered with respect to first stage (i.e., rotated around can axis).

[8] Smaller holes obtained by cylindrical band covering downstream half of 0.40″ holes, and stages staggered.

There are two important exceptions to can stability independence of downstream geometry. First, if a tailpipe is long enough to allow combustion to approach completion, flow and pressure oscillations may develop (i.e., "rough" burning). These oscillations can extinguish a flame that would be stable at the mean operating conditions. Second, any stage downstream of the recirculation zone may be close enough to the next stage upstream, or may allow enough cold mixture to enter, so as to quench the flame. Burning may not continue upstream of this stage. If it does continue, the over-all efficiency of the can will be quite low and burning, though "stable," is ineffective.

Details of recirculation zone design will be considered next.



Code	F	G	H	I	J	K
Open perimeter, %	13	26	33	42	59	83

Fig. 7 Effect of open perimeter on performance of 3-in. cans

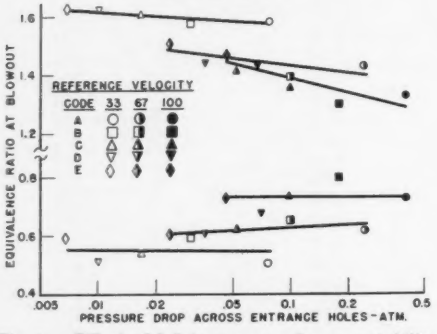


Fig. 8. Effect of inlet pressure drop on stability of 3-in. cans

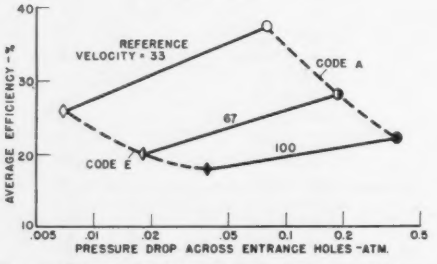


Fig. 9 Effect of inlet pressure drop on efficiency of 3-in. cans

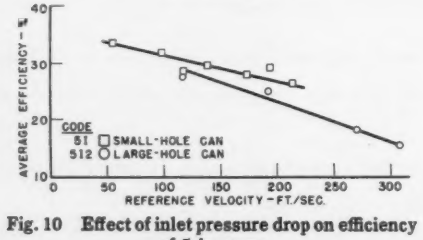


Fig. 10 Effect of inlet pressure drop on efficiency of 5-in. cans

Open Perimeter

Several variations can be made in the holes constituting the first stage. The total hole area can be changed as can the number and size of holes for any given total area. If the area is held constant, one may have many small holes or a few large ones. With many small holes, the open perimeter is large; with a few large holes the open perimeter is small. (The plane of the inlet hole centers intersects the can in a circle; the percentage of this circle occupied by holes is denoted the "open perimeter.") Tests were conducted with a series of seven 3-in. cans with equal total areas but with open perimeters ranging from 13 to 94 per cent. The results are shown in Fig. 7.

Limited efficiency data show an increase of efficiency as open perimeter drops from 60 to 26 per cent. A few other points (not shown) suggest a decrease in efficiency for open perimeters smaller than 26 per cent. Effects on efficiency almost vanish at high loadings—that is, at the highest reference velocity. Stability data show a definite trend toward wider limits at higher open perimeters. The only exception occurs for lean blowouts at the lowest reference velocity; however, these are the most scattered data. Points for the highest open perimeter can—Code L, with 94 per cent open perimeter obtained by narrow slots extending around almost the entire circumference—are not plotted because the data were very erratic.

Hole Size and Pressure Drop

In another series of 3-in. cans, five burners with different hole sizes were tested. Each burner had the same number of slots with a constant circumferential dimension. However, the slot axial length varied among burners, thus giving a constant open perimeter but varying total hole area. In the results following, one cannot distinguish between the effects of hole size and pressure drop per se; changes must be charged to the combined effects. The pressure drops used range from about 2 to 120 per cent of the control pressure. Most of this range is above the range acceptable in ramjet and turbojet practice.

Stability data for the 3-in. cans, plotted in Fig. 8, show slightly wider limits at lower pressure drops. However, the data of Fig. 9, for the two extreme configurations of Fig. 8, show lower efficiency at lower pressure drops. This result is confirmed in Fig. 10 by a comparison of two 5-in. cans—Code 5I and 5I2. The former can, with smaller holes, had about five times the pressure drop of the latter for a given reference velocity. Again, efficiencies are lower for the lower pressure drop can. Stability limits for these two 5-in. cans were about equal.

The 3-in. cans M and M1 were compared briefly; their geometries were the same except that M had eight 0.5-in. holes while M1 had four 0.5-in. holes. Thus, M had both lower pressure drop and higher open perimeter for a given reference velocity. Both properties should tend toward lower efficiency and wider stability limits. The tests showed that stability of M was better than that of M1; differences in efficiency were not significant.

Recirculation Zone Depth

Another geometric variable is the axial length of the recirculation zone between its upstream end and the plane of the first stage of inlet holes (see Fig. 2A). In cylindrical cans, stability becomes progressively worse as recirculation zone depth is reduced below the equivalent of about one can diameter. There is no change in stability (relative to that at depths of one diameter) for depths greater than one diameter.

These conclusions are well illustrated by the data of Fig. 11 for both 5-in. and 3-in. cans.

Cans P and Pa, both having no inlet air-directing shield and differing only in recirculation zone depth, gave the following equivalence ratios at lean blowout for the three reference velocities shown

Reference velocity	33	44	78
P (1 diam)	0.47	0.63	0.86
Pa ($^1/_2$ diam)	0.57	0.70	0.95

Again, the shorter can was less stable.

Data on recirculation zone depth effects on efficiency are less clear. As depth decreased from one diameter, efficiency appeared to drop slightly in both 3-in. and 5-in. cans. However, as depth increased from one diameter, efficiency appeared to increase slightly in 5-in. cans but decrease slightly in 3-in. cans. The term "appeared" is used because no exit plane total pressure surveys were made; thus, local efficiencies could not be weighted by local mass velocities.

Wall Temperature

One 3-in. can, Code M, was tested and found to operate with an average recirculation zone wall temperature of about 1000 F. The recirculation zone was then water jacketed (Code N) and resulting performance compared with the unjacketed can. The test data in Fig. 12 show that both stability and efficiency were impaired in the cooled can (with wall temperature of about 70 F). (The "relative efficiency" ordinate means data not weighted for local mass velocities.) Qualitatively, this would be expected no matter what burning mechanism is assumed to occur inside the recirculation zone. However, the effect is relatively small considering the radical change in wall temperature in these two cans.

Inlet Jet Direction

Three 3-in. cans, differing only in the shield geometry (see Fig. 2), were compared to assess the effects due to differences in inlet jet direction. Jets entered about normal to the pilot axis in the shieldless can and with either a downstream or an upstream velocity component in the shielded cans. Stability limits are plotted in Fig. 13. Differences in rich limits were small and are probably not significant. Lean limit data show best performance with downstream-directed jets. This is a reasonable result because such direction causes lighter loading of the recirculation zone (where flame stabilization presumably occurs) for a given reference velocity. Analogous reasoning leads one to expect the normal jet can to behave intermediately, but this can was actually poorest. The normal jet can had no shield and thus operated with negligible velocities upstream of the holes. Such a can would be more susceptible to burning upstream of the can (either because of local hot spots developing and igniting the outside mixture, or because of pulsations forcing flame back through one or more holes into the relatively stagnant surrounding mixture). Intermittent burning upstream would prematurely extinguish the flame in a random way. Such burning was observed experimentally; it was found that stability limits for the shieldless can were less reproducible than for either shielded can.

There are no data on the effect of inlet jet direction on efficiency.

Scale

Stability limits of single-stage cans of very similar geometries but of different diameters are shown in Fig. 14. The limits obviously widen as can diameter increases for a given reference velocity. If cans could be scaled by cross-sectional area, performance would depend on reference velocity only. But Fig. 14 shows that performance is more diameter dependent than is cross-sectional area; i.e., diameter appears as a parameter in Fig. 14. It will be seen below (Fig. 16) that stability does correlate well with u_0/D (where u_0 is reference velocity and D is can diameter) rather than with u_0 alone.

Pressure

Combustion pressure was varied from $^1/_2$ to $^1/_6$ atm abs in tests with a 3-in. can, Code I. Resulting performance is shown in Fig. 15. It is clear that efficiency decreases and stability limits narrow as pressure decreases. (However,

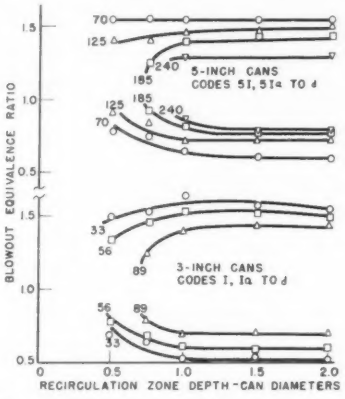


Fig. 11 Effect of recirculation zone depth on stability of 5-in. and 3-in. cans; parameter is reference velocity, ft/sec

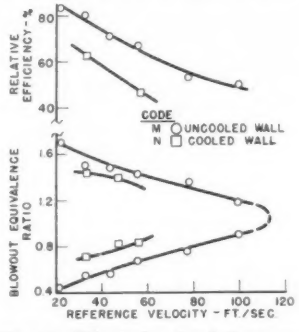


Fig. 12 Effect of recirculation zone wall cooling on performance of a 3-in. can

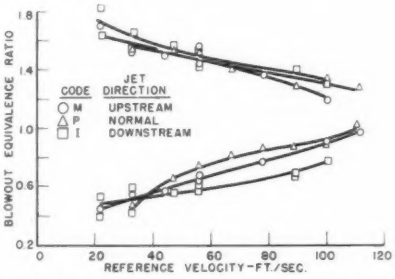


Fig. 13 Effect of inlet jet direction on stability of 3-in. cans

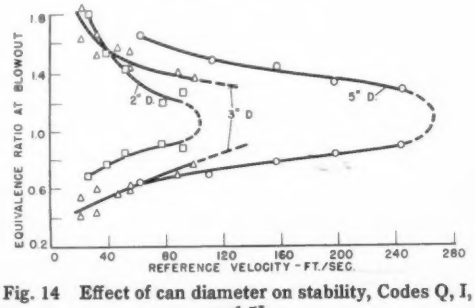


Fig. 14 Effect of can diameter on stability, Codes Q, I, and 5I

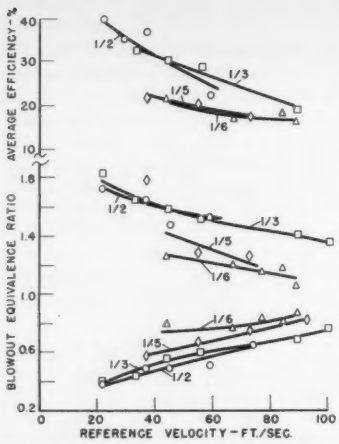


Fig. 15 Effect of pressure on performance of a 3-in. can, Code I; parameter is pressure in atm abs

it is likely that the effects of pressure are large only at subatmospheric pressures. Combustion is complexly controlled by a combination of mixing and chemical reaction rate. At high Reynolds numbers, mixing is fairly insensitive to pressure while reaction rate is very pressure dependent. At low combustion pressures, reaction rates are slow and are more likely to be limiting; if the limiting mechanism in a combustion system is pressure sensitive, the over-all system is pressure sensitive. At high pressures, reaction rates are rapid and mixing is more likely to be limiting; the insensitivity of mixing to pressure makes combustion less sensitive to pressure at high pressures.)

Data Correlation

The preceding blowout data on pressure and scale effects have been combined in a single empirical correlation in Fig. 16. The correlating abscissa was chosen to be $u_0/DP^{0.8}$, reference velocity divided by the product of can diameter and pressure to the 0.8 power. Although there is some variation among the curve slopes and positions, there is good correspondence among the maximum abscissas of each curve. The rounded dotted sections of the curves were not drawn completely arbitrarily. For each can size, the can was tested at an abscissa slightly higher than reached by the dotted curve. In each case, the can would not burn under such conditions. The dotted sections were drawn to complete the curves just short of these test abscissas where burning was impossible.

One expects some differences among the different can sizes due to heat losses, for example. Different sizes have different surface-to-volume ratios in the recirculation zone; thus, different fractions of heat would be lost, and it was shown in recirculation zone cooling tests, Fig. 12, that heat loss affects stability. In addition, because of the higher capacities required, the 5-in. cans were tested in a laboratory other than, but similar to, that used for the 2- and 3-in. cans. Differences in calibrations or test section geometry would affect the stability curve.

One possible stabilization mechanism in the can that could account for the type of empirical correlation observed is as follows: Assume that there is in the recirculation zone an intensely mixed region whose volume V is proportional to the volume of the recirculation zone C_1D^3. (C_1 and C_2 below are proportionality constants.) The piloting action of this region controls burning in the entire recirculation zone and thus in the entire can. In addition, the mass rate N at which gases enter and leave the intensely mixed region is assumed proportional to the rate at which mass enters the first stage $C_2u_0D^2P$. If the reacting volume V is very vigorously stirred, a homogeneous combustion reaction will occur and the stability of this stirred region will depend on the over-all kinetics of homogeneous reaction. It has been shown (3) that such kinetics correlate by plotting the blowout equivalence ratio against the group $N/VP^{1.8}$. But it was assumed above that $N \sim C_2u_0D^2P$ and $V \sim C_1D^3$ so that, substituting, $N/VP^{1.8} \sim u_0/DP^{0.8}$. Therefore, the correlating group of Fig. 16 is, in fact, the same group used to correlate the blowout data of the intensely mixed spherical reactor of (3).

A second possible stabilization mechanism also results in dependence on over-all reaction rates but without requiring a stirred zone homogeneous in composition and temperature. In this mechanism, a circulation path exists within the recirculation zone. Gases almost completely burned enter the path while mixing rapidly with unburned gases also entering the path. The mixture than burns progressively along the path from a relatively low initial efficiency to a high final efficiency. Local rates of burning are the over-all reaction rates corresponding to local values of composition and temperature. Such a model again leads to blowout behavior similar to that observed in the spherical reactor.

If either of the afore-mentioned models is reasonable, the spherical reactor blowout curve, with all abscissas multiplied by the proper proportionality constant, should approximate the can blowout data. The dotted curve of Fig. 16 thus shows the spherical reactor curve with the multiplying constant selected to best match the can data. (Fitting the 3-in. can data was emphasized because of the greater number and believed greater reliability of these data.) The dotted curve chosen does match the 3-in. rich data very well; however, the curve slope is too small for a good match to the 3-in. lean data. Curve slope is determined by apparent activation energy E of the over-all combustion reaction. In the spherical reactor, E was found to be about 42,000 cal per mole. The lean 3-in. can data here would be matched best by a curve corresponding to an E of roughly 35,000. However, it is likely that the mismatch results not from use of the wrong E but from inaccuracies in the mechanism assumed. For example, it is quite certain that the recirculating fraction of gases entering the first stage is not exactly constant as reference velocity changes. Therefore, that part of the recirculating fraction which enters the intensely stirred controlling region is not exactly proportional to first-stage mass flow, i.e., C_2 is not always constant. Similarly, the constant C_1 probably changes somewhat as geometry and operating conditions change. Finally, recirculation zone heat losses act complexly, and the effects of heat loss have not been considered in the simple adiabatic reaction rate mechanism assumed. A combination of these several effects accounts for

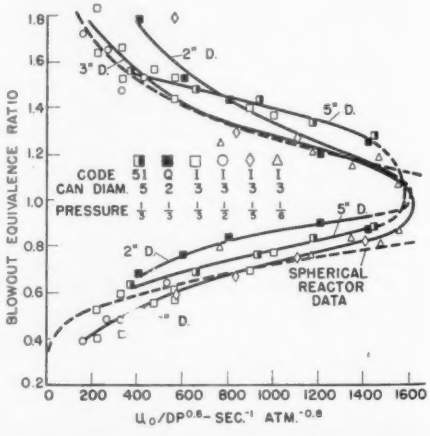

BLOWOUT EQUIVALENCE RATIO
3" D.
2" D.
5" D.
CODE 51 Q 1 1 1 1
CAN DIAM. 5 2 3 3 3 3
PRESSURE 1/3 1/3 1/3 1/2 1/3 1/6
SPHERICAL REACTOR DATA
$u_0/DP^{0.8}$ - SEC.$^{-1}$ ATM.$^{-0.8}$

Fig. 16 Empirical correlation of can blowout data

the fact that the spherical reactor curve gives a reasonable approximation to the data but not an exact match.

It is interesting to note that in the region immediately around stoichiometric, all of the can curves are rounded and pinch off while the spherical reactor curve extends out (to a maximum abscissa of about 2300). However, in this region the operable range—between rich and lean curves—is very narrow. Small fluctuations may put the can temporarily outside this range and prematurely extinguish the flame. A quite rounded stability curve near stoichiometric is observed with most combustion equipment, and the very smooth-burning spherical reactor was almost unique in not showing such rounding.

Efficiencies measured in the 3-in. can run at various pressure levels were noted in Fig. 15. If the data are plotted using the same correlating group as Fig. 16, the curve of Fig. 17 results. The variables affecting can stability thus combine in a similar way to affect efficiency. The falling off of efficiency at larger abscissas is partly due to a decrease in efficiency in the controlling stirred region in the recirculation zone (due to higher loading of the region, cf. (3)) but primarily due to decreasing ability of the hot gases discharged from the recirculation zone to spread flame—through the unburned gases that did not recirculate—in the short tailpipes provided.

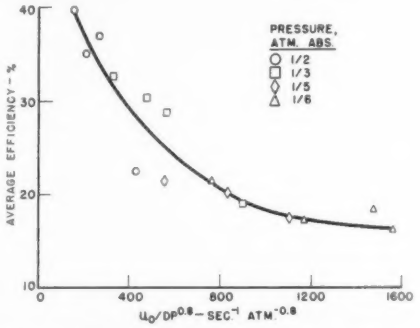


Fig. 17 Empirical correlation of 3-in. can efficiency data; data of Fig. 15 replotted

As the abscissa reaches its maximum value of about 1600 (beyond which burning is not possible), the efficiency tends to level off at about 16 per cent. If one assumes that all the burning took place in the recirculation zone (subsequent flame spreading is negligible), the recirculation zone heat release corresponding to the efficiency of 16 per cent and $u_0/DP^{0.8}$ of 1600 is about 19,000 Btu per sec per cu ft of recirculation zone volume per $atm^{1.8}$. In the same units, the spherical reactor heat release, near an equivalence ratio of 1.0, was about 83,000. Thus, if the burning does occur in a homogeneously reacting region within the recirculation zone, this region occupies only about 23 per cent of the total zone volume. Stated otherwise, a fourfold improvement in recirculation zone heat release is possible by provision of a mixing pattern more closely approaching the spherical reactor pattern.

Blowout data for 2-, 2.5-, and 3-in. single-stage cylindrical cans burning at $\frac{1}{3}$ to 1 atm abs have been published (4) by White and Lewis of NGTE. To correlate their results, they chose a group corresponding to $u_0/P^{0.5}D^{0.4}$; this group shows less dependence on pressure and diameter than the $u_0/P^{0.8}D$ used here. Although their group did correlate their lean blowout data quite well, it failed almost completely to correlate their rich data. In analyzing the differences between the NGTE results and these, it is important to keep in mind the differences in operating conditions at blowout, as summarized in Table 1.

Equivalence ratio ranges in Table 1 include every data point reported for all geometries, air rates, pressures. Note that the NGTE results do not include any data in the equivalence ratio range from about 0.7 to 1.3 where the greatest sensitivity of stability range to operating conditions exists. The pressures used extended from 10 to 30 in. Hg abs, with most of the data taken at pressures higher than 10 in. In addition, these pressures were measured downstream of the burner, suggesting that the recirculation zone static pressures were even higher than those recorded. For comparison, the Esso blowout data always included near-stoichiometric mixtures, but the over-all stability ranges were narrower. Almost all the testing was at pressures of 10 in. and below, with only a few points run at the maximum pressure of 15 in. One additional difference was the 200 C inlet temperature at NGTE compared to the 200 F (93 C) here. This temperature increase will double the over-all reaction rate at an equivalence ratio of 0.5, according to (3).

All of the differences in operating conditions outlined above are qualitatively correct in explaining the differences in results. That is, the NGTE data show less sensitivity to changes in conditions and show larger permissible loadings. However, this is not to assert that all differences in results are accounted for. At present, there is no complete explanation for these differences. It would be interesting to have efficiency data from the NGTE burners to see whether the heat release rates obtained are as high as the superficial stability data might suggest.

Miscellaneous Effects

In all of the preceding data where mass flow (or reference velocity) has been increased with other conditions constant, a narrowing of stability limits and a decrease in combustion efficiency have resulted. Therefore, no additional data to illustrate this point are required.

It is also well known that addition of tailpipe length increases efficiency, simply by allowing more time for combustion. This has been illustrated in the profiles in Fig. 3. The efficiency increase observed on adding a given length depends on many variables, e.g., the initial efficiency, reference velocity, pressure, temperature and velocity profiles, and so forth. There is not enough known to accurately generalize the effect.

Although lighter loading of a recirculation zone increases can stability in a multistage can, over-all efficiency may suffer. In general, it is desirable to load the recirculation zone as heavily as possible consistent with meeting stability requirements. This principle is illustrated in Fig. 18 giving results from three two-stage 2-in. cans differing only in the ratio of first-stage to second-stage hole area. When the greatest proportion of total flow entered the first stage, over-all efficiency was highest. As more of the flow was diverted from first to second stage, efficiency dropped.

A few tests were made with two-stage 2-in. cans in which the second row of holes was rotated around the can axis so as to be staggered with respect to the first row holes. No

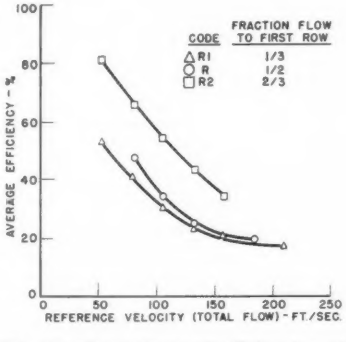


Fig. 18 Comparison of efficiencies of two-stage 2-in. cans with various area ratios

difference in efficiency or stability was observed when compared to similar cans in which the holes were in line. This suggests that, at least for the geometries (see Table 2) and operating conditions tested, the flow and burning patterns are essentially axially symmetric.

Acknowledgment

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The Design of Cylindrical Propellant Grains

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The mathematics of the design of a cylindrical propellant grain is discussed in general. Only the directrix of the cylindrical burning surface (the intersection of the cylinder with a plane normal to its lateral surface) need be studied. During burning, the evolute of the directrix is invariant. A cusp convex toward the gas phase remains a cusp. A cusp concave toward the gas phase becomes an arc of a circle. The rate of increase or decrease of the length of an arc free from cusps depends only on the inclination of the arc at its end-points. The design of an internally burning propellant grain is discussed in more detail, and a method is described for designing a grain in which the burning surface area is a prescribed function of the portion of the web thickness burned through.

Introduction

ALL publications on the subject of propellant grain design which have come to the writer's attention imply that grain shapes are arrived at by the mathematical testing of proposed designs. In particular, cylindrical grains are usually bounded by portions of planes and right circular cylinders. The aim of this study was to find deductive mathematical methods of propellant grain design and to explore the use of surfaces other than the plane and the right circular cylinder. The problem has been solved only for the special case of the cylindrical grain.

A solid propellant grain burns in such a manner that any point on its surface moves inward perpendicularly to the tangent plane at that point and at a burning rate which depends on the temperature of the grain and on the pressure of the gas in contact with it. It will be assumed in what follows that erosive burning and pressure drop along the grain are negligible. The burning rate may then be assumed to be constant over the entire surface. In this paper, only the cylindrical grain will be considered.

If the cylinder is interesected by a plane perpendicular to its lateral surface, it will be sufficient for us to study the changes which the curve of intersection, or directrix, undergoes during burning. This point of view is applicable if the cylindrical grain is cut at both ends perpendicular to its lateral surface and inhibited on these end surfaces to prevent burning there.

On the directrix, a cusp convex toward the gas phase remains a cusp as burning progresses (Fig. 1). A cusp concave toward the gas phase, however, becomes an arc of a circle with its center at the original cusp (Fig. 2).

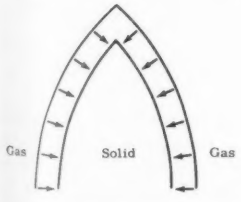

Fig. 1 **Effect of burning on a convex cusp**

Fig. 2 **Effect of burning on a concave cusp**

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On a portion of the directrix which has no cusps, for every point on the directrix (apart from singularities) there is a corresponding center of curvature. These centers of curvature fall on a smooth curve, called the evolute of the directrix. If a flexible, inelastic string is wound around part of the evolute and the loose end is pulled taut, the length of this loose end can be adjusted so that its end-point falls on the directrix. Then, as the string is wound on, or unwound from, the evolute, the end-point traces out the directrix. The proof of this proposition can be found in almost any textbook of advanced calculus.

If the new form of the directrix is to be constructed after the burning surface has advanced a distance u into the grain, the loose end of the string is shortened (if the burning surface is convex) or lengthened (if the burning surface is concave) by an increment of length u; and the string is again unwound from, or wound on, the evolute. Hence, the evolute remains unchanged during burning.

The circle and the straight line are both degenerate cases. The evolute of the circle is a single point, its center, and the straight line is a degenerate circle with center at infinity.

As the burning progresses on a portion of the directrix which is convex and free from cusps, the point of maximum curvature will be first to reach the evolute. At that instant, this point will turn into a cusp. The sequence of events is then the reverse of that shown in Fig. 2.

Fundamental Theorem

Again, on a portion of the directrix which is free from cusps, at any point, let φ be the angle between the tangent to the directrix and a fixed direction in space, and let κ be the curvature of the directrix at the same point, so that $R = 1/\kappa$ is the radius of curvature at that point. Then κ or R may be expressed as a function of φ. The length s of the directrix may be measured from a fixed point on the directrix to the point under consideration. By definition

$$\kappa = \frac{d\varphi}{ds} \quad [1]$$

whence

$$ds = d\varphi/\kappa = R\, d\varphi \quad [2]$$

Now, let R be a single-valued continuous function of φ over the portion of the directrix under consideration. (It will be shown presently that this does not mean a loss of generality.) Let φ_1 and φ_2 be the values of φ at the two end-points of this portion. Then the length of the portion is

$$s = \int_{\varphi_1}^{\varphi_2} R\, d\varphi \quad [3]$$

Consider the portion of the directrix lying between $\varphi = \varphi_1$ and $\varphi = \varphi_2$ and suppose that burning has progressed to the point where R has increased by a constant increment u. (R and u have opposite signs for a convex burning surface.) Let s' be the new length of this portion of the directrix. Then

$$s' = \int_{\varphi_1}^{\varphi_2} (R + u)\, d\varphi = s + u(\varphi_2 - \varphi_1) \quad [4]$$

Hence, the change in length of this portion of the directrix depends only on the values of φ at the ends and not on the nature of the function $R(\varphi)$.

If $R(\varphi)$ has a finite number of discontinuities, such as points of inflection of the directrix, the directrix may be subdivided at these points, and s' may be calculated separately by Equation [4] for each of the resulting portions and summed over the whole curve. Note that u has the same value for all of these portions. (At a point of inflection, R changes sign.) The value of φ_2 of any portion equals the value of φ_1 of the next portion, so that the terms $u\varphi_1$ and $u\varphi_2$ pertaining to the junctions cancel. Only the terms pertaining to the end-points remain, so that Equation [4] remains valid as long as the directrix has no cusps.

Although the reasoning which led up to Equation [4] is not valid for a straight line segment, the conclusion is still valid where some of the portions of the directrix are straight line segments. Only if a straight line segment forms an extremity of the curve does this conclusion become invalid, since then φ_1 or φ_2 would not uniquely define the end-point.

If the directrix is a closed curve, it may be broken at any one point and treated by Equation [4]. In this case, $\varphi_2 = \varphi_1 + 2\pi$. The rate of increase in length of a closed directrix without cusps, therefore, does not depend on its length or form. Only the percentage rate of increase in length depends on the instantaneous length, being smaller in absolute value for a longer curve.

Practical Considerations

If the outer surface of a cylindrical grain is uninhibited and has no cusps, the grain is regressive-burning. Likewise, an uninhibited cylindrical perforation without cusps is progressive-burning, and by the same amount. Hence, a tubular grain is neutral-burning. The resulting design has been widely used. However, rocket motors with long burning times have made thermal insulation of the motor wall imperative. A simple solution to this problem is to inhibit the outer surface of the grain by bonding it to the motor wall. Such a grain burns on the surface of an internal perforation only. The grain will be progressive-burning unless the surface of the perforation has cusps, in which case it may be progressive-, neutral-, or regressive-burning.

In practice, the requirements on the form of a propellant grain are more stringent than the above considerations would indicate. Any grain not bounded solely by right circular cylinders coaxial with the motor wall must change its burning characteristics before it is completely consumed. This will happen when the thinnest portion of the grain has burned through, when a point of maximum convex curvature has become a cusp, or when an inhibited portion of the grain has burned to the center of the inhibitor and detached itself. Maintaining an approximation of the prescribed burning characteristics from this point on makes great demands on the designer's ingenuity.

Grain With Linear Burning Characteristics

Fig. 3 shows the design of an internally burning grain developed at Aerojet-General Corporation. Since this grain has convex cusps, it is not necessarily progressive-burning. The directrix consists initially only of straight line segments (curve A), but arcs of circles develop at once in place of the concave cusps (curve B). Eventually, the straight line portions are consumed and only the circular arcs remain (curve C). This form undergoes a further modification when the thinnest portions of the grain burn through and the motor tube is exposed (curve D). Stage C may be eliminated, as has been done in the Aerojet grain, by making the motor tube narrower in proportion to the dimensions of the initial curve A. (Calculating the lengths of these curves requires only elementary mathematics.) The design parameters are

Fig. 3 Neutral-burning grain designed at Aerojet-General

the angle θ at which two rectilinear portions meet to form a convex cusp, the number of points of the star, and the ratio of the length of a rectilinear portion of curve A to the radius of the motor tube. While the directrix has the form B, its length is a linear function of u and will be a constant for a seven-pointed star with $\theta = 71.0$ deg. To continue with this latter example, the curve C will increase in length, but only slowly at first. Curve D is strongly regressive. This design is almost perfectly neutral-burning.

General Method of Design

A more general problem is the design of a propellant grain so that the thrust, and therefore the discharge rate of the exhaust gases, is a given function of time. For a given choice of propellant, the discharge rate is a known function of chamber pressure. This in turn is a known function of burning surface area for a given design of the rocket motor. The details of these calculations have been adequately described in (1).[2] Let $\dot{m}$ be the mass rate of discharge of gases (mass per unit time), S_0 the surface area, u the distance into the grain through which the burning surface has penetrated, ρ the density of the propellant, and t the time. Then

$$u = \int \frac{\dot{m}}{\rho S_0}\, dt \qquad [5]$$

Thus S_0 and u can be determined as functions of time, and S_0 can be expressed as a function of u. Since this can be calculated from the design specifications, a given function $S_0(u)$ will be taken as the starting point of the discussion which follows. The problem is to design an internal-burning grain (such as that of Fig. 3) having an arbitrary integral number (in this case seven) of identical lobes, with each lobe possessing an axis of symmetry, and to determine the curve bounding half of the lobe.

Fig. 4 shows the notation to be used. Since the directrix is symmetrical, the convex cusp at the tip of a lobe moves along a straight line as burning progresses. The curve which borders half a lobe terminates at a cusp, and the line along which this cusp advances is taken as the y-axis of a rectangular coordinate system. The position of the x-axis is arbitrary. In Fig. 4, it is supposed that the unburned propellant lies above the curve, so that the curve advances in the direction of increasing y as burning progresses.

Initially, the curve is of the form ABC, shown schematically in Fig. 4. The point A is the initial position of the cusp, and C is the initial position of the apex of the lobe. Let φ be the inclination of the curve at any point B. At A, the value of φ is φ_1, and at C it is φ_2. These angles are positive as shown in the figure, but actually φ_2 is always negative. Now let n be the number of lobes. Then $\varphi_2 = -\pi/n$. Let the initial

[2] Numbers in parentheses indicate References at end of paper.

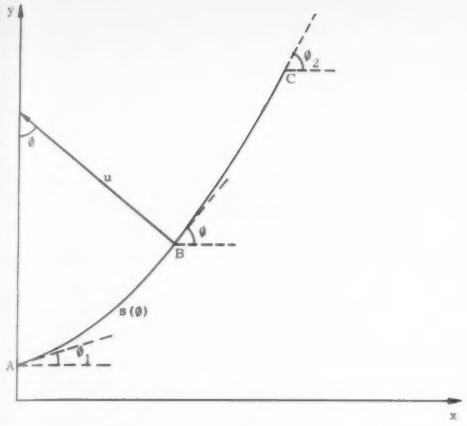

Fig. 4 Notation used in the design of internally burning grains

length of the arc AB be $s(\varphi)$. Then $s(\varphi_1) = 0$, and the total initial length S of the curve AC is $s(\varphi_2)$.

When the burning surface has advanced into the grain through a distance u, the point B has moved to the cusp. Thus, the inclination φ at B may be regarded as a function of u. Now only the portion BC of the curve remains. Its initial length was $S - s(\varphi)$, but its length at the instant under consideration is found from Equation [4] to be

$$S'(u) = S - s(\varphi) + u(\varphi - \varphi_2) \quad \ldots\ldots [6]$$

(The seeming discrepancies between Equations [4] and [6] are due to the fact that the origin from which s is measured and the sign convention for c were not specified in connection with Equation [4].) Let l be the length of the cylindrical grain at right angles to the plane of Fig. 4, and let n be the number of lobes as before. Then

$$S' = S_0/2\,ln \quad \ldots\ldots [7]$$

which is a given function of u. The problem is then to determine s and the coordinates x and y of the general point B of the initial curve—all as functions of u.

Differentiation of Equation [6] yields

$$dS' = -ds + u\,d\varphi + (\varphi - \varphi_2)\,du \quad \ldots\ldots [8]$$

From geometrical considerations and elementary calculus

$$x = u \sin \varphi \quad \ldots\ldots [9]$$

Hence

$$dx = \sin \varphi\,du + u \cos \varphi\,d\varphi \quad \ldots\ldots [10a]$$

$$dy = \tan \varphi\,dx \quad \ldots\ldots [10b]$$

$$ds = \sec \varphi\,dx = \tan \varphi\,du + u\,d\varphi \quad \ldots\ldots [11]$$

Substitution for ds from [11] into [8] yields

$$dS' = -\tan \varphi\,du + (\varphi - \varphi_2)\,du \quad \ldots\ldots [12]$$

whence

$$\frac{dS'}{du} = \varphi - \tan \varphi - \varphi_2 \quad \ldots\ldots [13]$$

Since S' is given as a function of u, the left-hand member of Equation [13] is known. Equation [13] may then be solved numerically for φ.

In Fig. 3, the curve bounding half a lobe terminates in a straight line segment. Hence Equation [4], and with it the reasoning which led to Equation [13], is invalid in this special case. Nonetheless, Equation [13] remains valid. This will be seen from the fact that $dS'/du = \text{const}$, which yields Fig. 3, may be approached as a limiting case. In the case of the neutral-burning grain, $dS'/du = 0$. In the case of Fig. 3, $n = 7$. Then $\varphi_2 = -0.449$ radian. Hence $\varphi = 0.951$ radian $= 54.5°$. The angle θ of Fig. 3 is given by $\theta = 180° - 2\varphi = 71.0°$, in agreement with the above.

In general, dS'/du will not be constant, and the design problem may be solved as follows. The derivative dS'/du must first be tabulated. If $S'(u)$ is known only in the form of tables, this must first be done by numerical differentiation. Next, Equation [13] is solved numerically for φ for every entry in the table. The angle φ is differentiated numerically with respect to u. The functions $\sin \varphi$ and $\cos \varphi$ are tabulated. Then, from Equations [10a], [10b], and [11], dx/du, dy/du, and ds/du can be obtained. They are integrated numerically to yield $x(u)$, $y(u)$, and $s(u)$. Finally, y is plotted against x to yield the desired curve. Its total length is given by the last entry for s in the table. If this is less than the prescribed S, an adjustment must be made by the addition of an arbitrary curve at the end. However, this curve must be free from convex cusps and must join all adjacent curves without convex cusps. If the required adjustment in length is negative, a larger number of lobes n may be helpful. However, for negative values of dS'/du, the initial length S must be kept above a certain minimum.

If on the other hand dS'/du is positive, the number of lobes n must be made sufficiently small, or negative values of φ may be required. These negative values would create a curve crossing over on itself, which has no physical meaning.

Calculation of the port area, if desired, requires only elementary mathematics. The only difficulty which requires a word of explanation is the evaluation of the integral $\int y\,dx$. Since u rather than x is used as the independent variable throughout, the integral must be written in the form $\int y \cdot (dx/du)\,du$. Since y and dx/du are tabulated as functions of u in the course of the design work, the integrand can be evaluated and integrated numerically.

As an example, Fig. 5 shows the design of a grain to the specifications $S' = 9 - \frac{1}{2}u + \frac{1}{8}u^2$ and $\varphi_2 = -\frac{1}{4}\pi$; that is, $n = 4$. This grain is initially regressive-burning. The burning surface, and hence the nozzle area ratio, the chamber pressure, the burning rate, and the thrust, reaches a minimum; then increases. During the final sliver stage, corresponding to curve D of Fig. 3, the prescribed characteristics cannot be adhered to, and burning will then always be strongly regressive.

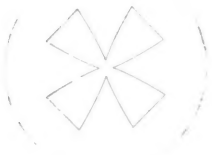

Fig. 5 Internally burning grain designed to the specification $S' = 9 - \frac{1}{2}u + \frac{1}{8}u^2$

In conclusion, this method makes possible the design of a cylindrical powder grain having any prescribed burning characteristics within certain limitations. The result usually is a curve not made up entirely of straight line segments and/or arcs of circles. While such a curve is costlier to produce, the added cost may be worth while in certain practical applications.

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Jets—Review of Literature[1,2]

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Introduction

THE review deals with the fundamentals and mathematical theory of free boundary flow and jet; with the distribution of velocity, density, pressure and temperature in laminar jets; transport of mass, momentum and energy in turbulent jets; and with closely related phenomena—the acoustical ones, designing of nozzles, orifices, wind tunnels with open jets, etc., being excluded. The review is divided into eight sections.

1 Fundamentals and Mathematical Theory of Free Boundary Flow and Jets

Basically, one may refer the investigations of jets to Torricelli, Daniel Bernoulli, and Borda; and to a remarkable series of papers by Savart, Sondhauss, Masson, v. Helmholtz, Hanlon, Froude and Thomson, Kirchhoff, Rayleigh, etc. Borda's mouthpiece and *vena contracta* are discussed by v. Helmholtz, Lamb, Birkhoff, and others. Fundamentals of free boundary theory are thoroughly discussed by Helmholtz, Kirchhoff, Chaplygin, Levi-Civita, Villat, Cisotti, Weinstein, Hamel, Poole, Weyl, Bergman, Friedrichs, Demtchenko, Leray, Jacob, Valcovici, Pérès, Kravtchenko, Lavrentieff, Oudart, Theodorsen, Shiffman, Birkhoff, Gilbarg, Serrin—with references to works on axially symmetric jets by Weingartner, Trefftz, Schach, H. Reissner, Marchet, Southwell and Vaisey, and others; on penetration by liquid jets by Worthington, Gilbarg and Anderson, Birkhoff and Caywood; on some theorems on wakes extended to jets like those of Leray, culminating earlier works of Weinstein and Friedrichs, generalized by jets by Kravtchenko (see also Villat, Brodetsky, etc.); on compressibility effects in jets by Caius; on jet sucked around a bend by Lighthill; on re-entrant jet by Gilbarg and Rock, Efros, Arnoff, and others; on wall correction in some special cases by Valcovici, whose equations were re-derived by Birkhoff, Plesset and Simmons; on surface of discontinuity by Hadamard, Klein, etc.

2 Distribution of Velocity, Density, Pressure, and Temperature in Supersonic and Submerged Jets

The problem of the theoretical distribution of velocity in jets was attacked long ago by Bazin, Emden, Chaplygin, and others. Laminar flow of a two-dimensional incompressible fluid was solved by Schlichting, Bickley, and Okabe (see also v. Mises and Friedrichs, p. 186). The measurements by Andrade confirmed these calculations. Analogous approach in compressible fluid was applied by Abramovich, Krzywoblocki, Pai, Chapman, and Toose. A laminar axially symmetrical jet in incompressible fluid was solved analytically by Schlichting, experimentally measured by Andrade and Tsien, and generalized to compressible fluid by Krzywoblocki. Asymptotic expansions to wakes and jets were used by Krzywoblocki, relaxation method by Southwell. The turbulent spreading of two-dimensional jets was calculated by Tollmien; a simpler approach was proposed by Görtler, Huang, and Lin—symmetrical plane jet on the vorticity transfer theory by Howarth, Lord; measurements by Förthmann, Peters, and Bicknell (see Rossby) and Reichardt. Turbulent axially symmetrical jet was calculated by Tollmien, Grodzovskii, Squire, and Pai; measurements performed by Zimm, Ruden, Juethe, Reichardt, and Wuest. Calculations of a circular jet on the vorticity transfer theory have been made by Tomotika, Howarth; measurements by Viktorin. Spread of a turbulent mixing of a stream of fluid with fluid at rest, the mixing taking place along a single boundary between them (in German *freie Strahlgrenze*) has been calculated by Tollmien, generalized to the case of two streams with different velocities by Kuethe; Torda, Ackermann and Burnett took into account the influence of upstream boundary layers on the mixing process, but Sears did not agree with this approach. Tollmien compared his solution with measurements in the nozzle of the Göttingen wind tunnel; some tests were performed by Reichardt. Temperature distribution in laminar jets both plane and circular has been calculated by Krzywoblocki; in turbulent flow by Howarth; experiments by Ruden. For more details see Goldstein (145–8; 592–9; 672–3) and Schlichting (1951: 137–40; 152–4; 446–7; 452–6). Other writings on the velocity distribution in jets are by: Betz, Okaya and Hasegawa, Garside, Kunze, Schaefer, Liepmann, Corrsin and Laufer, Deodati and Monteath, Kiseley, Lin, Squire and Trouncer, Whitmore, and others. Heated and thermal air jets are treated by Schmidt, Corrsin, Cleeves and Boelter, Corrsin and Uberoi (direct verification of Kolmogoroff's hypothesis). Supersonic jet has been discussed by Hachette, Frankl, Ladenburg, Sauer (characteristics method), Winkler, Gooderum, Pack, Coburn, Owen and Thornhill; submerged jet by Rumer. Modern hypotheses on free boundary flows may be applied to jets as well: Townsend, Batchelor, Crocco, Lees, Corrsin, Kistler, etc.

3 Transport of Mass, Momentum and Energy; Diffusion in Turbulent Jets; Entrainment of Air; Injectors

The literature on transport of mass, momentum and energy, on diffusion in turbulent jets, etc., is extensive: Betz and Petersohn, Ledgett, Predvoditeleve and Slupotschenko, Bicknell, Cordes, Hawthorne, Binnie (water), Pabst, Minchin, Yagi, Jeschke, Szablewski, Lenhart and Wohl, Citrini, Liepmann and Laufer, Weatherston, Baron, Collins and Newby, Taylor, Corrsin, Holdhusen, Collins and Tyler, Forstall, Hinze and Van der Hegge Zignen, Hough, Schlinger and Sage, Shapiro and Forstall, Yih, Pool and Charyk, Alexander, Baron, Comings, Kivnick, Bershader and Pai, Forstall and Shapiro, Landis, Landis and Shapiro, Little and Wilbur, Comings and Grimmett, Chilton and Generaux, etc. Entrainment of air is discussed by Trupel, Thomas and Evans, Townend, Voorheis, and Tuve. Principles of air injector are treated by Bailey and Bauman.

4 Jet Mixing of Two Fluids; Parallel and Multiple Jets

Jet mixing of two liquids has been treated by Moss, Folsom and Ferguson, Newby and Thring, Fossett and Prosser, Sänger, and Pai. Parallel jets have been treated by v. Bohl, Corrsin, Ferguson, Holt, Shapiro, Kawamura, Szablewski, Thompson and Torda, Torda, Ackermann and Burnett, and others; multiple jet interaction, by Jonas.

5 Jet and Perpendicular Stream, Impinging of Jets on Obstacles, Interaction between Jets and Surfaces

Penetration of liquid jets into a high velocity air stream is discussed by Chelko; jet and perpendicular air stream by Chang-Lu, Callaghan and Ruggeri, Lu, Ruggeri, Morkovin, Pierce and Craven; impinging of jets on obstacles by Willis, Greenhill, Bouasse, Schach, Prandtl and Tietjens, Milne-Thomson (who refers to Schieldrop), Leclerc, Birkhoff, Rapoport, Slezkin, Gurevič, Pack and Roberts; interaction between jet and body surface by Kuchemann, Kunze, and Jonas.

6 Sonic, Cavitation, and Capillary Phenomena; Waves in Jets; Pulsations, Perturbations, Stability

Sensitivity of jet to sound has been discussed by Savart, Brown; sonic combustion by Bodine; cavitation phenomena by Roesler, Arnoff; novel properties of "water bells" by Hopwood; capillary phenomena by Rayleigh, Lamb, and Ericksen; waves in jets by Rayleigh, Lamb (p. 472), and Kai; shock waves in jets by Prandtl, v. Kármán, Pack, and Kawamura. To account for Emden's experiments with axial jets, Prandtl developed linear theory and performed some tests; recently Pack reconsidered Prandtl's formula for the wavelength. Standing surface waves have been discussed by Rayleigh,

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[3] Professor of Gas Dynamics and Theoretical Aerodynamics, University of Illinois; and Consultant, Physics Division, NOTS.

Wada; stability by Rayleigh, Tyler, Lamb, Foote and Lin, Pai, Bellin, Messin and Richards, and Graham; stability of Bunsen burners by Bollinger and Williams; of velocity distribution by Roberts and Meigh, Chiarulli, Chiarulli and Lin; of mixing region between two parallel streams by Lin; pulsation by Robinson, Chichester; perturbations in transonic and supersonic range by Guderley; disintegration of jet into drops by Smith and Moss, Bond and Newton, Tyler, Littaye, Merrington and Richardson, Hinze, Borodin and Dityakin, Panasenkov, Richardson (p. 100), etc.

7 Ejectors, Thrust Augmentors, and Flow Coefficients

Flow in ejectors is discussed by Third, Scott and Jamieson, Work and Haedrick, Work and Miller, Smith, Kispert, Elrod, McClintock and Hord, Ellerbrock, Miller, McCloy, Reid, Yen, and others; ejector thrust by Grad, Sanders and Brightwell, and Christophe; thrust augmentors by Jacobs and Shoemaker, Schubauer, Lee, Campbell, Morrison, and v. Kármán; flow coefficients by Bowden, Callaghan and Bowden.

8 Effect of Jet on Airplane Stability, Application of Jet Theory to Practical Purposes

The effect of jets on stability of jet airplanes has been treated by Ribner, Blackaby. The list of references contains many papers on the application of jet theory to injector burners, atmospheric gas burners, Bunsen burners, steam jets, inlets of ventilation, overfire air jets, wind tunnels, etc. Incomplete reviews of the literature on jets are due to Forstall and Shapiro with some additions by Krzywoblocki and Spielman, and to Alexander. An excellent review of flow through nozzles is by Redding.

General Remarks

The symbols *AMR* 2, Rev. 889 mean that the paper in question was reviewed in *Applied Mechanics Reviews*, vol. 2, Review no. 889.

The abbreviations for titles of periodicals and reports, cited in the Bibliography, follow the key to abbreviations used in *Applied Mechanics Reviews*. The references are ordered alphabetically.

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ADDENDUM

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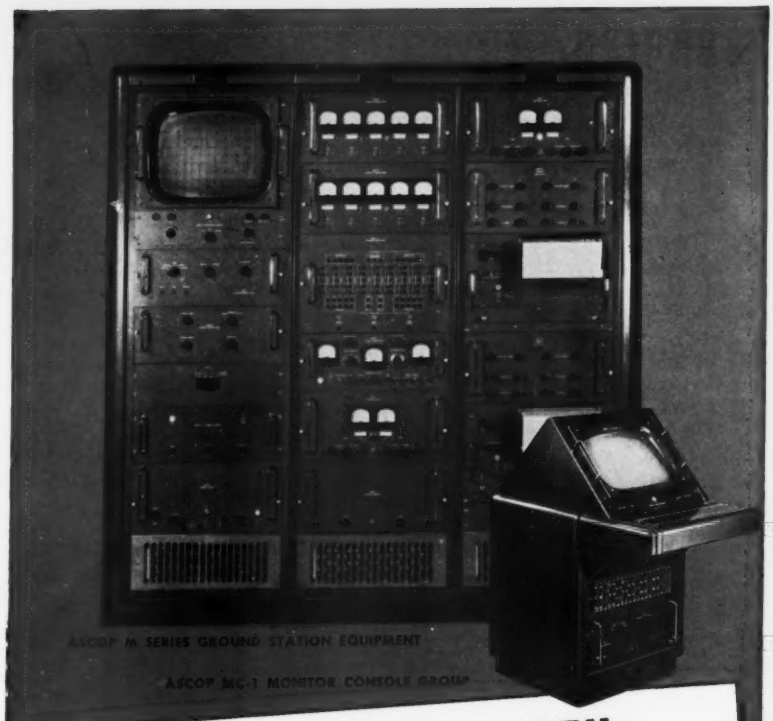

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Technical Notes

A Note on Transpiration Cooling

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STUDY of transpiration cooling in many of its aspects has resulted in a voluminous and complex literature. Much of this has to do with the evaluation of heat transfer coefficients at the fluid-porous solid interface. This note describes some interesting consequences of a set of particular assumptions that describe a one-dimensional model. The model is believed to be of practical use.

Weinbaum and Wheeler (1)[2] gave the correct solutions for the wall temperatures but ignored fluid boundary layers. This required knowledge of wall surface temperatures and resulted in equations of some complexity. These are drawbacks for engineering use. A valuable result of their studies was the demonstration that solid and coolant temperatures were very close to each other within the porous structure.

Mayer and Bartas (2) developed the equations under the explicit assumption of equality of fluid and porous solid temperatures. However, their model included a term for heat convection at the coolant entrant side. This involves the difficulties of evaluating the convection coefficient for a flow that has a net velocity perpendicular to the wall as well as parallel to it. Similar difficulties exist at the hot gas or coolant exit side. Eckert (3) suggests a model that implies no heat transport parallel to the porous surface by the coolant fluid outside it. This would be the case of flow of the coolant being only perpendicular to the wall at the entering side—or, at least, the relative flow perpendicular to the wall being enough to make the heat transport parallel to the wall negligible. Schneider (4) gives the results for such a one-dimensional flow. His equations involve the wall temperature at the hot side but do not carry the balance on to involve the hot side gas temperature and hot side film coefficient.

It is believed that the case of one-dimensional coolant flow through a porous wall to a hot gas side will approximate many engineering problems.

By assuming substantial equality between T_w and T_c we can write

$$-Gc_p \frac{dT}{dx} = K \frac{d^2T}{dx^2} \quad \ldots\ldots [1]$$

This applies to the entire wall since the distance n to l is shown by Weinbaum and Wheeler (1) to be very small indeed.

Equation [1] can be integrated for the boundary conditions

$$h_g(T_g - T_0) = -K(dT/dx)_{x=0} \quad \ldots\ldots [2]$$

$$h_g(T_g - T_0) = Gc_p(T_0 - T_{ci}) \quad \ldots\ldots [3]$$

where K represents the thermal conductivity of the porous, coolant-filled structure and h_g is an equivalent coefficient allowing for convective heat transfer in the hot gas boundary layer, radiation to the wall, and enthalpy increase of the coolant fluid emerging and mixing in the boundary layer.

The general solution of Equation [1] is

$$T = C_1 + C_2 e^{-as} \quad \ldots\ldots [4]$$

$$a = Gc_p/K \quad \ldots\ldots [5]$$

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[2] Numbers in parentheses indicate References at end of paper.

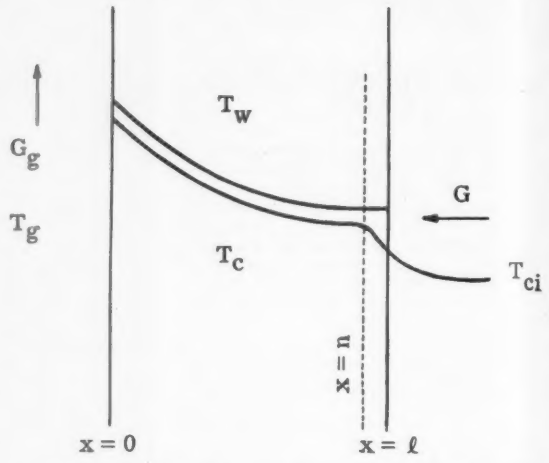

Fig. 1 One-dimensional model showing definitions of symbols

For the boundary conditions [2] and [3]

$$C_1 = T_{ci} \quad \ldots\ldots [6]$$

$$C_2 = \frac{N_g}{1 + N_g}(T_g - T_{ci}) \quad \ldots\ldots [7]$$

$$N_g = h_g/Gc_p \quad \ldots\ldots [8]$$

The efficiency of transpiration cooling is defined as

$$\eta_1 \equiv \frac{T_g - T_0}{T_g - T_{ci}} = \frac{1}{1 + N_g} \quad \ldots\ldots [9]$$

The temperature drop through the wall is of interest for engineering purposes

$$\eta_2 \equiv \frac{T_0 - T_l}{T_g - T_{ci}} = \frac{N_g}{1 + N_g}(1 - e^{-al}) \quad \ldots\ldots [10]$$

The third component of the total temperature difference is

$$\eta_3 \equiv \frac{T_l - T_{ci}}{T_g - T_{ci}} = \frac{N_g}{1 + N_g} e^{-al} \quad \ldots\ldots [11]$$

It is interesting to note that from the above results

$$\frac{\eta_2}{\eta_1} = N_g(1 - e^{-al}) \quad \ldots\ldots [12]$$

which is the same result as obtained by Mayer and Bartas (2) with allowance for heat loss at the coolant side. They pointed out possible use of this ratio for comparing hot side coefficients with and without transpiration.

The equations given above should permit calculations for engineering cases more easily than earlier, more complex versions requiring coolant side coefficients.

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Demonstration of Reliability in Liquid Propellant Rocket Engines

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Introduction

A RELIABILITY development program for liquid propellant rocket engines can be generalized as consisting of two distinct efforts, the first of which is to evolve or develop a system which is believed to have a specified reliability, and the second, to determine with some degree of assurance that the specified reliability has been achieved. These two efforts go hand in hand, with the first unable to proceed without the second. Yet, it is the second effort, i.e., the proof of a system's reliability, which is of greater concern to liquid rocket engine contractors.

In the minds of many people, the familiar and established techniques for the development of reliability are contained within the development history of the piloted aircraft. Hence, to clarify the nature of the problem it is helpful to refer to the circumstances which have prevailed throughout the history of liquid propellant rocket engine development and note how these differ from those of the piloted aircraft. These are briefly outlined as follows:

1 There has been a consistent lack of propellant, components, and system design standardization. This, coupled with only limited production which tends to restrict refinement of the successful powerplants, has prevented the accumulation of reliability know-how both in design and production.

2 The liquid rocket engine is used mostly with large and expensive missiles in which the cost of a rigorous flight reliability program is often considered prohibitive. This denies, to the designer, important information concerning how various component design types actually behave under various missile flight conditions.

3 The environments in which the liquid propellant rocket engine and its components will operate can only be approximated prior to flight testing, and adequate telemetered information concerning these cannot always be obtained during flight tests. Further, these environmental conditions tend to be different for each new missile application of the rocket engine.

The above circumstances are in obvious contrast with those of the piloted aircraft. In particular, flight testing is not so limited by budget considerations and, in fact, the piloted aircraft provides an economical in-flight laboratory wherein the components can be observed for improvement under actual conditions. Lack of this advantage is one of the major obstacles facing those concerned with the development of components for the guided missile. No matter how carefully the design and development program has been conducted, the specified reliability of the engine system can be realized only in missile flight tests appropriately designed for the purpose. Considering the expense of these flights, however, it would not be economically feasible to begin such a program unless the engine system and other components had been developed and evaluated to a specified value of reliability in a suitable static test program. Without this, the flight tests could all too readily degenerate into a costly component reliability program.

Recently, the development of the guided missile and its liquid propellant rocket engine has been accelerated for several tactical applications. Hence, it becomes increasingly important that reliability development is accomplished through the use of additional methods and techniques. We believe the solution to this problem, in part, can be realized by including in each engine development program a reliability effort which is suggested by the definition of reliability.

Fundamentals of a Reliability Program

Reliability of a liquid propellant rocket engine is defined as the probability that there will be no failure of the unit to operate within design performance limits.[3] This definition suggests that the science of statistical analysis be utilized since it is necessary to follow statistical theories in questions of probability. Certainty cannot result from this, but only a degree of assurance that any given standard of reliability has been achieved. This degree of assurance in itself is a probability and is referred to as statistical confidence. The definition also indicates that the rocket engine system should have the inherent ability to operate consistently within its design performance limits before a measurement or a demonstration of its reliability is attempted. With this assumption, the probability of success of the system then depends upon its ability to withstand the detrimental environments to which it will be subjected throughout its useful life.

This suggests that the reliability of the rocket engine system be evaluated by testing within the most severe environments anticipated, and the resulting data analyzed by statistical methods.

Although it will invariably be necessary to estimate the types and magnitude of the environmental conditions, rocket engine systems which have been submitted to such procedure will certainly produce a more fruitful flight test program. It is to be expected that these flights will reveal errors in the assumption of the environmental conditions. This will effect reappraisal of the assumed environments, and redevelopment of engine components to meet these new conditions.

To include a rigorous reliability effort as part of a development program will increase the cost. However, it is firmly believed that this increased cost will be more than offset by a reduction of future development work on the missile itself. This fact may not always be fully appreciated in the early stages of a missile program. It is, therefore, prudent to design an economical reliability program commensurate with military budgets, but still yielding sufficient data to provide a statistical basis for reliability.

The proper choice of the statistical techniques can help in reducing the cost of a reliability demonstration program. There are several methods and combinations of methods which can be useful, the choice among which depends upon judgment with respect to the problem at hand. For example, the size and complexity of the system to be evaluated may render one method more suitable than another, or reliability under certain environmental conditions may be evaluated more readily by one method than another.

A reliability program resulting from an application of statistical methods is seen to be a broad and complex subject when described adequately to cover all applications of liquid propellant rocket engines. We will only generalize on some of these methods and point out a type of statistical testing which we have found to be most useful in the reliability demonstration phase of an engine development program.

Reliability and the Development Cycle

Let us assume that we are charged with the design and development of a typical liquid propellant rocket engine which the bid specifications state should be developed to a reliability of 96 per cent with a 95 per cent statistical confidence in the result. This engine is to power a guided missile and,

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[2] Project Engineer, Experimental Projects Dept.

[3] In order that an engine system reliability program may be an efficient part of the missile reliability program, these performance limits should be only those which, if exceeded, would cause the missile to deviate from its performance limits.

therefore, its mission will be to start, operate within specified tolerances, and stop—only once. That is, a so-called one-shot device. However, in practice it must undergo several tests at the engine manufacturer's plant and also at the launching site.

To be effective and realistic, the reliability program for this engine must start at the beginning of a developmental program and play a major role throughout. To illustrate this, let us look at the five major phases of a development cycle as shown in Fig. 1.

The Design Phase

During the design phase the rocket engine system and its components should be under continuous scrutiny to insure consistency among all aspects of the design and the requirements of reliability. System analysis would be concentrated on the reduction of the complexity of the system since complexity is a major factor of the time and cost required to achieve a specified reliability. Here, sound engineering judgment can be a factor in reducing the cost and complexity of a reliability program by:

1 Designing the rocket engine system to have inherent reliability, i.e., substituting systems having inherent characteristics for those requiring complex controls. For example, complex thrust chamber controls and safety circuits can oftentimes be eliminated by propellant choice and/or unique design arrangement among the injector, propellant valves, and system.

2 Choosing designs favoring reliability, even though compromises must often be made with regard to maximum performance and minimum weight. Here, missile designers can help, as they are prone to specify such high powerplant performance that a propulsion system having critical characteristics is often necessary to meet the specifications.

3 Utilizing design concepts proved to be reliable in past programs on similar systems, and rejecting questionable design approaches or those that may require an excessive amount of development time. Thus, the desire to improve the art must be tempered by reliability requirements as well as development schedules.

The engine system illustrated in Fig. 2 is an excellent example of the use of the above design concepts. This helicopter auxiliary powerplant (ROR) brings proved concepts to a new application. It achieves inherent reliability by virtue of its simplicity and the use of catalytic rather than electrical ignition means. Admittedly, it is not the highest performing system which could be designed. However, it is sufficiently high to perform its job well. It has achieved a record of 99.5 per cent reliability over approximately 2500 flight operational cycles.

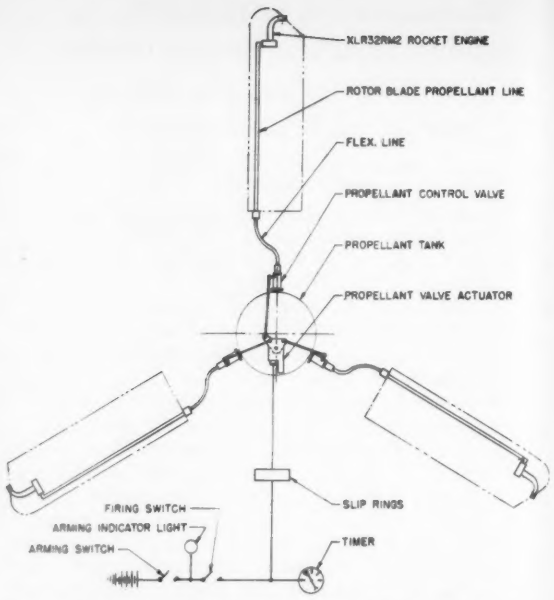

Fig. 2 ROR schematic diagram as applied to HRS-2 helicopter

The Development Testing Phase

The development testing phase will be directed primarily toward achieving a prototype design which has the inherent ability to perform in accordance with the required specifications, even under environmental extremes. It is within this phase that the reliability of each component under simulated conditions is improved until it approaches a preassigned value consistent with the over-all system reliability figure. Judgment must be exercised to concentrate only on those components or subsystems whose operating conditions can truly be simulated by bench testing, such as solenoid valves, pressure switches, etc.

The Proof Testing Phase

The proof testing phase of the development program concerns those tests which are routine requirements of all newly developed units and which must be performed before the unit may be considered ready for flight. The proof testing phase includes acceptance, flight approval, and qualification tests. The latter two may be conducted prior to or coincident with the reliability demonstration phase.

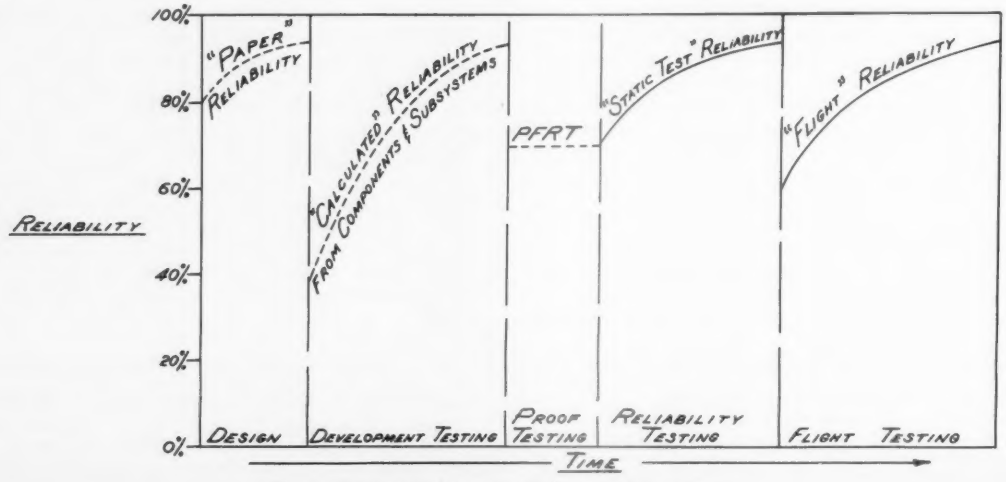

Fig. 1 Typical liquid rocket engine reliability history

The Reliability Testing Phase

This newest phase of a developmental cycle is becoming known as the reliability demonstration phase in bid specifications for rocket engine systems. Within this phase, the sequence of engine system reliability evaluation, improvement, and re-evaluation within simulated environmental conditions in static testing takes place until the specified reliability has been demonstrated.

The Flight Testing Phase

This phase of the program should be conducted parallel with the reliability testing phase as it is important that the unexpected environmental conditions that are encountered in flight be fed back into the reliability testing phase. Only in this way will an efficient over-all reliability program result.

The remainder of this paper deals with the problem of demonstrating that the specified reliability has been achieved on an engine system by a program of static testing which should be conducted prior to, and continue throughout, the missile flight test program.

Statistical Methods

The type of data which can be analyzed statistically to determine reliability may be derived from two general types of testing classified as testing by attributes and testing by variables. Testing by attributes concerns itself only as to whether a sample is, or is not, within specifications. In reliability evaluation the system would be operated within a selected environmental condition and the number of times the unit operated, or did not operate, within the specified limits would be the basis for analysis.

Testing by variables is concerned with the actual value of the measurements and how they vary one sample to another. For reliability evaluation, the system would be operated with the simulated environmental conditions increased in severity for each run. The levels at which the system ceased to operate within specifications would constitute the data which would be subject to statistical analysis to determine the probability of failure under the maximum environmental level expected in service. This type of testing is sometimes referred to as test to failure and is not generally favored for system testing, as it can involve difficult and expensive test procedures. On the other hand, this method can be used effectively, in many cases, for evaluation of the individual components of the system in the earlier part of the development program.

The data which result from either of these two types of testing can be obtained by several sampling plans, the choice among these depending upon which serves the best interests of the program. Obviously, the best interests are served when the testing plan is such as to provide the most information for the least cost. Every test that is made on a large liquid propellant rocket engine system is expensive as is the test installation itself. Therefore, a method is desired which permits testing to terminate as soon as sufficient data have been accumulated from which a decision as to the reliability of the system can be made without requiring complicated manipulation of the environmental conditions. It is believed that these conditions are realized by testing the rocket engine system in a program of testing by attributes following the methods of sequential analysis.

Sequential analysis is a relatively recent addition to statistical science, the details of which are adequately outlined in current texts. Briefly, the method is based: First, on the premise that the sample size, or in our case the number of tests required, is an independent variable and for fixed risk limits the expected number of trials is a minimum. Second, the number of observations needed to decide quality with a given risk between two specific postulated values is less than that required to decide between one value and all possible alternatives. With this method it is not necessary to be concerned with other statistics, such as distributions or variances.

The manner of its use consists of conducting a series of tests within a simulated environmental condition and noting the number of successful and nonsuccessful tests as they occur in sequence. After each test, the probability of observing such a sequence of events with respect to the specified reliability (R_1) and some other alternative value (R_2) is calculated by means of the likelihood ratio (P_2/P_1) after which one of three decisions can be made: (a) The specified reliability has been demonstrated; (b) an alternative reliability value is indicated and therefore the system has not demonstrated the specified reliability; (c) sufficient observations have not yet been made to come to any decision and a further test must be made.

Fig. 3 shows a plot of the likelihood ratio equated to the risk limits which can be used rather than making calculations

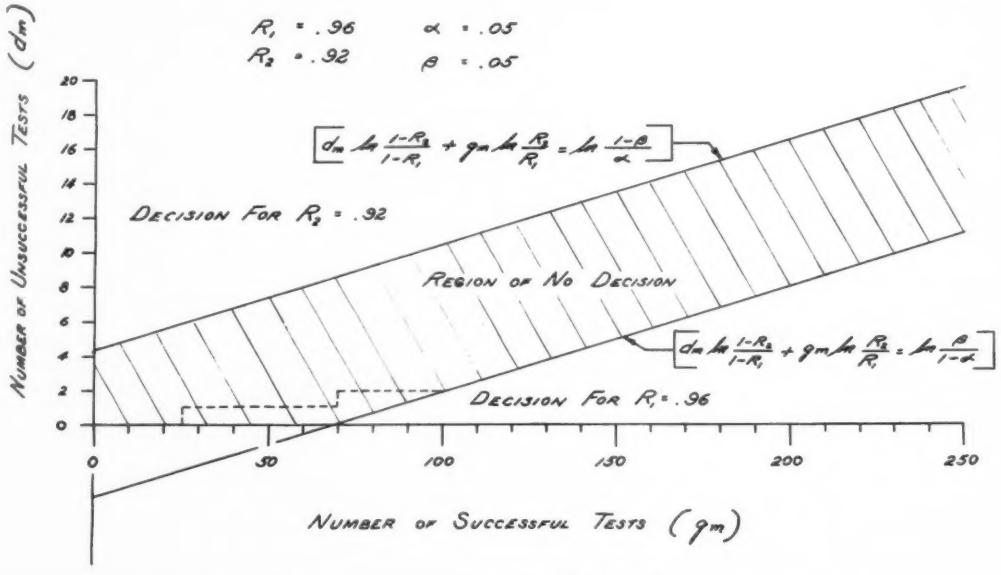

Fig. 3 Chart of the likelihood ratio $\frac{P_2}{P_1} = \frac{(1 - R_2)^{dm} (R_2)^{gm}}{(1 - R_1)^{dm} (R_1)^{gm}}$ equated to risk limits

after each test. On this graph an example is shown of 25 successful tests, an unsuccessful test, followed thereafter by 45 successful tests, another unsuccessful test, and then 30 successful tests, which resulted in a decision that the specified reliability has been demonstrated.

The limits for the probabilities upon which the above decisions are based are known as the alpha (α) and beta (β) risks. The value of α represents the probability that the engine system will be rejected by the testing plan even though its true reliability equals the specified reliability ($R = R_1$) and is known as the producer's risk. The value of β indicates the probability that the engine system will be accepted by the testing plan although the true reliability does not equal the specified reliability ($R \neq R_1$) and is known as the consumer's risk. The value for this risk is indicated in the bid specifications by the statistical confidence desired in the reliability evaluation and is equal to that value subtracted from one. For our engine system, $\beta = (1.00 - 0.95) = 0.05$.

With the specified reliability (R_1) and the consumer's risk (β) fixed by the bid specifications, the average (and minimum) number of tests required to reach a decision in the sequential analysis depends upon the values selected for the alternative reliability value (R_2) and the producer's risk (α), and becomes less with smaller values of R_2 (Fig. 4) and larger values of α. Judgment must be exercised in selecting these values. The value for α is selected by the contractor from economic considerations and the risk he is willing to take of having the system rejected when, in fact, it has the specified reliability. The value of R_2 should be judged from the prior knowledge of the approximate system reliability which can be derived from the component reliability evaluation during the early part of the program and the relationship that exists between the components and system reliability. In other words, the amount of testing of the system will depend upon how completely the component reliabilities were determined. With the values of R_1, R_2, α, and β established, the average sample number equation as shown in Fig. 4 can be used, together with suitable contingency factors, for estimating the scope of the test program for budgeting purposes.

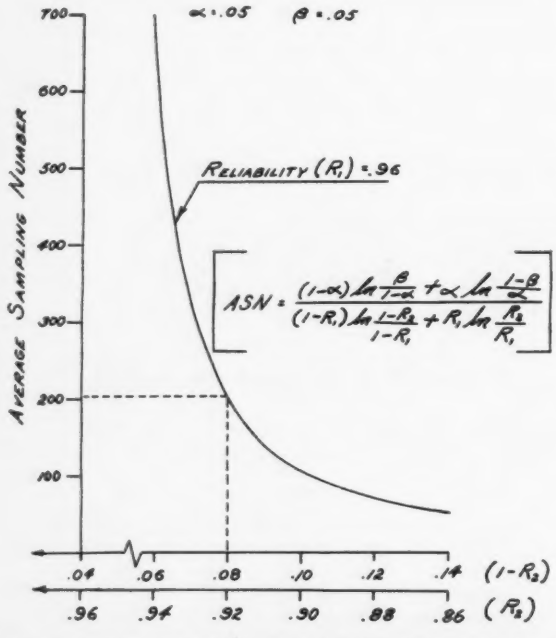

Fig. 4 Average sampling number vs. alternative values (R_2)

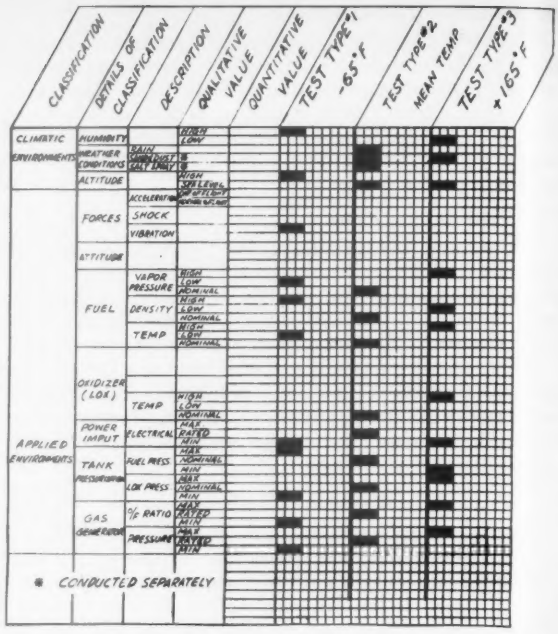

Fig. 5 Environmental survey chart

Conducting the Reliability Program

The stipulated conditions within which the test program is to be conducted are fundamental to the reliability program since it is against these conditions that the demonstration of reliability is made. Here, some judgment must be exercised in combining certain environmental conditions such that they represent the most likely combinations detrimental to reliability. These combinations form groups of conditions, or test types, within which the sequence of tests is performed.

The cost of the reliability program depends a great deal upon how extensively these environments are selected. Comprehensive selection would involve a broad range of environments including those associated with transportation and storage along with those which are expected when the rocket engine system is in operation in the missile.

For the purpose of this demonstration we have assumed that a limited environmental coverage is desired. That is, only those environments most likely to be encountered in starting, running at specified conditions, and stopping during flight or ground checkout operations of the missile. The environmental conditions judged detrimental to the rocket engine system are arranged as shown in the environmental survey chart of Fig. 5. In this case the environmental groupings result in three test types with temperature considered to be the predominant environment of each. The shaded blocks indicate the combinations of climatic and applied environments which can occur simultaneously in the application to produce the most adverse operating conditions.

The extremes of temperature can be applied rather simply by the method illustrated in Fig. 6. In this manner the propellants and the atmosphere surrounding the missile propulsion system can be conditioned to the desired temperature prior to each test run. The set of three mobile conditioning units can serve an entire test area and can be applied to a variety of missile or rocket engine equipment. Fig. 7 illustrates a propellant conditioning unit now in use in the RMI rocket test facility.

The number of engine system components required for the testing program, including the allowable expendables, should be procured preferably by random selection from a

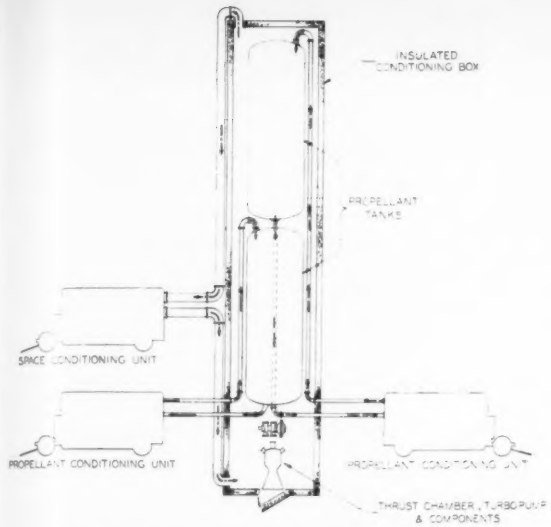

Fig. 6 Conditioning unit functional schematic

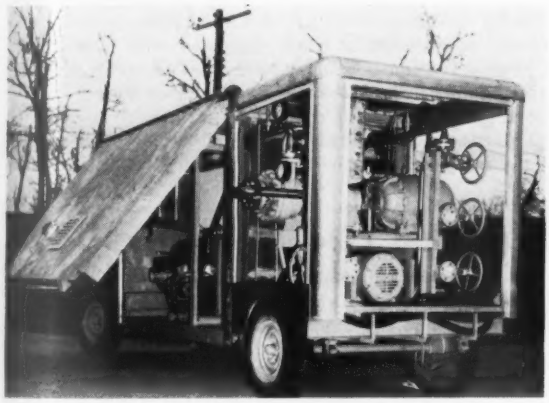

Fig. 7 RMI propellant conditioning unit

larger production quantity. From these components, three engine systems would be assembled for the sequential testing, one for each test type, and first subjected to acceptance tests since all engine systems must survive these and subsequently be reliable in the field. Thereafter, the systems would be subjected to the sequential testing within the conditions of the test type to which each assembly has been assigned and the number of successful and nonsuccessful runs tabulated as previously described.

During the course of the sequential testing the engine system will periodically accumulate running time equivalent to that of its useful service life. To avoid the possibility of wear-out becoming a factor of the reliability evaluation, the system at these intervals should be subjected to routine overhaul procedures. Since these servicing procedures would be the same as those specified for the production system, they can be considered one of the environments of the testing program and, in general, consist of tear-down, inspection, and the replacement of specified components in reassembly. The requirement for replacement of any component beyond that allowed by these procedures would be deemed a performance failure.

Results of the Reliability Testing Plan

Now, let us consider what can be expected to be established by the reliability testing plan for this engine system. Results that could be of interest might include: (a) reliability of a particular engine system design, (b) reliability of a typical production engine system, (c) reliability of a limited number of typical engine systems for repeated operation.

It would appear that (c) is the result that is to be expected; yet, it is the first two which are desired. From a consideration of the assumptions upon which statistical methods are based, statements can be made relating the results of the test program to the reliability of the engine system design and future production engines. Three important assumptions are as follows:

1 It should be equally likely that the engines selected have a reliability either superior or inferior to the average of all engines produced, or that can be produced under similar circumstances.

This assumption is often difficult to meet under the circumstances of limited production. However, if the total quantities required for the proof testing phase, the reliability demonstration phase, and the preliminary flight test program can be arranged as a production run, and the units chosen at random from this run, then a close approximation to this assumption can be realized.

2 The observations of the statistical test program must be independent, i.e., the probability of the outcome of each test should not be influenced by the previous test.

Here it is necessary to assume that the tests are, in fact, independent and, except for the wear-out effect of accumulative running time, this is a fair assumption. The testing plan described above was designed with cognizance of the possible wear-out effect.

3 The systems making up the future production quantity are to be produced by operations which are in statistical control, i.e., the unavoidable variations arise only from a constant system of chance causes.

The means by which this is accomplished is by the application of a production statistical quality control plan, based upon the component design tolerances found satisfactory during the earlier development program.

On the basis of the original assumptions, the results of such a test program then do indicate that the engine system design can result in future systems having 96 per cent reliability within the environments assumed. The results also indicate that 95 per cent of all engines to be produced under circumstances similar to those which produced engines tested will meet the specified reliability.

Summary

To summarize, we have described some of the reliability difficulties which plague the liquid propellant rocket industry, and how a statistical approach can be applied to the reliability demonstration phase of a development program even though the production quantities are small, the cost of testing is high, and some of the environmental conditions of the testing are assumed. Engine systems which have been submitted to this procedure will help make subsequent missile reliability flight programs more fruitful. Information from these flight tests concerning the environment and reliability of the engine system should be the basis for a continuing static reliability development testing program.

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Combustion of Fuel Droplets in a Falling Chamber With Special Reference to the Effect of Natural Convection

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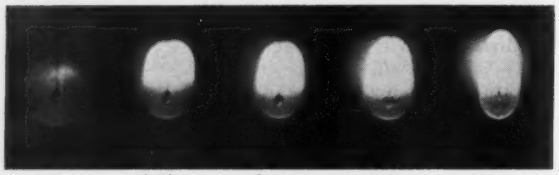
MANY investigations have been made experimentally and theoretically on combustion of fuel droplets. The results of these investigations are fairly useful for scientific researches and practical problems. Nevertheless, the author is sceptical about the previous works. All the theories are essentially similar, although they differ from each other in trivial points. There are several facts which cannot be explained by the theories mentioned above. Furthermore, it is surely meaningless to compare the experimental results obtained under the influence of natural convection with the theories based on a combustion model of spherical symmetry. There are two methods to avoid the effect of natural convection on combustion of fuel droplets. One is to observe combustion of extremely fine particles of fuel, and the other is to burn fuel droplets of ordinary size in a freely falling chamber.

This note briefly presents experiments using a combustion chamber devised so as to fall down with constant acceleration.



$0g$ $0.06g$ $0.11g$ $0.25g$ $1g$

Fig. 1 Flame shapes of n-heptane droplets when acceleration is varied from $1g$ to $0g$

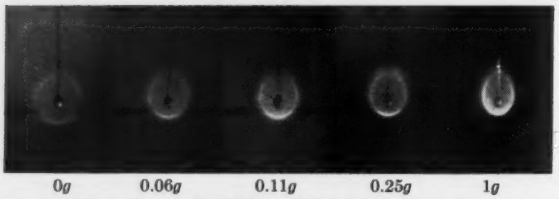


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Fig. 2 Flame shapes of ethyl alcohol droplets when acceleration is varied from $1g$ to $0g$

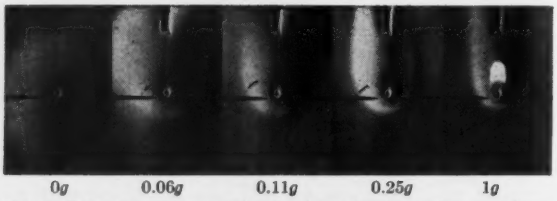

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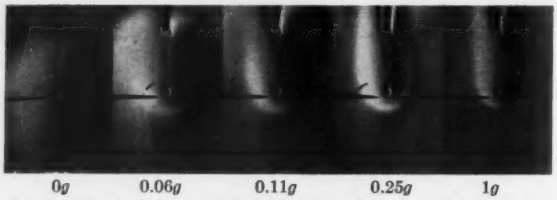
Fig. 3 Hot air zones around n-heptane droplets when acceleration is varied from $1g$ to $0g$



$0g$ $0.06g$ $0.11g$ $0.25g$ $1g$

Fig. 4 Hot air zones around ethyl alcohol droplets when acceleration is varied from $1g$ to $0g$

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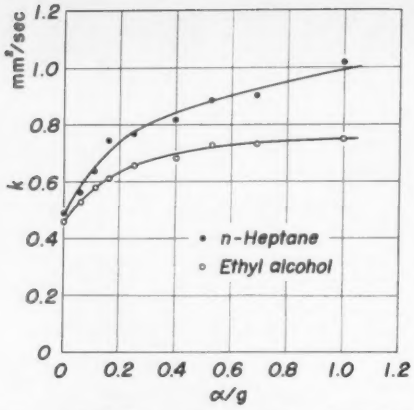

Fig. 5 Effect of acceleration on the evaporation constant

Figs. 1 and 2 show the change of flame shapes of n-heptane and ethyl alcohol, respectively, when acceleration is varied from $1g$ to $0g$. There are reproduced in Figs. 3 and 4 schlieren photographs of the bot air zone around the flame. Fig. 5 shows the effect of acceleration α on the evaporation constant k. It is found that the value of k in the case of no convection is considerably small compared with that under ordinary conditions. The experimental data obtained in such a manner can reasonably be compared with the theoretical predictions about combustion of fuel droplets.

This paper will be detailed by the author and his co-worker at the Sixth International Symposium on Combustion to be held at Yale University.

Empirical Prediction of Turbulent Boundary Layer Instability Along a Flat Plate With Constant Mass Addition at the Wall

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The incompressible turbulent boundary layer characteristics along a flat plate with constant mass addition at the wall were studied in a small wind tunnel in which the free stream velocity was varied from 20 to 150 ft/sec. Velocity profiles were measured for several positions along the porous plate for injection ratios of $0 < V_o\rho_0/U_\infty\rho_\infty < .01$. It was observed that at a specific value of $V_o\rho_0/U_\infty\rho_\infty$ at constant Re_x the boundary layer was effectively detached from the plate. An examination of the experimental data indicated that a blowing parameter of the form $(V_o\rho_0/U_\infty\rho_\infty)Re_x^{1/5}$ could be established which would reduce the results to a single curve when plotted as a function of $(C_f/2)Re_x^{1/5}$. The curve intersected the abscissa at $(V_o\rho_0/U_\infty\rho_\infty)Re_x^{1/5} \cong .08$ and appeared to give negative values of the skin friction. Certainly the existence of negative values of the shear stress is impossible, but the fact that the friction coefficient is reduced to zero with increased blowing rates does indicate the point at which the boundary layer is "blown off" the wall. This knowledge may provide some insight into optimum flow requirements for transpiration cooled surfaces. A comparison of the experimental results of other investigators indicates agreement with the present findings and suggests that a new approach to the analytical investigation of the transpiration cooling problem be used.

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Nomenclature

C_f = local fanning friction factor
Re_x = length Reynolds number
ν = kinematic viscosity, ft²/sec
U_∞ = mean flow stream velocity, ft/sec
Vo = injection velocity, ft/sec
ρ_0, ρ_∞ = density of injected fluid and primary fluid, respectively
Eu = Euler number

AN EXPERIMENTAL investigation is being conducted to answer several of the crucial questions pertaining to the problem of heat and mass transfer into a turbulent boundary layer. The results of the initial phase of the work served to establish the operating parameters and limits of experimental interest and to establish further the operating characteristics of the experimental equipment.

The existence of a turbulent boundary layer was established by mean velocity profile measurements in the absence of blowing. The effects of roughness over the porous plate seemed to be negligible. Both the impermeable and porous plates with no blowing yielded results that were in accord with the local friction factor for turbulent flow over a flat plate.

A family of velocity profiles was obtained with constant wall velocity, which exhibited a marked change in slope and finally an inflection point for increasing mass rates. Further increases in blowing rates gave a series of S-shaped profiles, indicating the possible detachment of the boundary layer from the wall. Measurements of the local skin friction were made using a modifed Stanton tube as described by Preston (1).[2] The observation served to confirm the belief held by the author that it was possible to determine a critical blowing parameter for the turbulent boundary layer above which detachment occurred. To determine the existence of such a parameter, velocity traverses were made for several stream Reynolds numbers Re_x and blowing ratios, $Vo\rho_0/U_\infty\rho_\infty$. By varying the stream velocity from 20 ft/sec to 150 ft/sec at zero Euler number over the plate and increasing the injection parameter $Vo\rho_0/U_\infty\rho_\infty$ to 0.01, it was possible to ascertain the point of incipient separation. At increasing values of stream velocity the point of detachment occurred earlier for a constant injection ratio.

Emmons and Leigh (2) have described the situation for the laminar boundary with uniform mass addition and indicated that the critical blowing parameter is reached when

$$Vo\rho_0/U_\infty\rho_\infty\sqrt{Re_x} = .619$$

and the skin friction tends to zero. For the incompressible, turbulent boundary layer the dimensionless friction parameter $(C_f/2)Re_x^{1/5}$ was plotted against the group $(Vo\rho_0/U_\infty\rho_\infty)Re_x^{1/5}$. The $^1/_5$ power of the Reynolds number Re_x appeared to be a reasonable choice in view of the relationship for the skin friction for the impermeable flat plate $C_f/2 = .0289\ Re_x^{-1/5}$. Fig. 1 shows the resultant data from present experimental work as well as the best available data obtained from Davis and Mickley (3). It is observed that the skin friction data tends to zero at a value of $(Vo\rho_0/U_\infty\rho_\infty)Re_x^{1/5} \approx 0.08$. The calculated friction factors at values greater than 0.09 for the blowing parameter appear to give negative values as shown in Fig. 1. The scatter in this region is large, indicating the uncertainty of these measurements. In all probability the pilot tube had been affected adversely by vertical velocity components and no longer served as an adequate means of determining the mean velocity profile. The analyses of Rubesin, Mickley, and others (4, 5) suggest an asymptotic solution for increasing values of the blowing parameter. Thus the inadequacy of the present one-dimensional analysis for describing the transpiration phenomenon becomes apparent.

[2] Numbers in parentheses indicate References at end of paper.

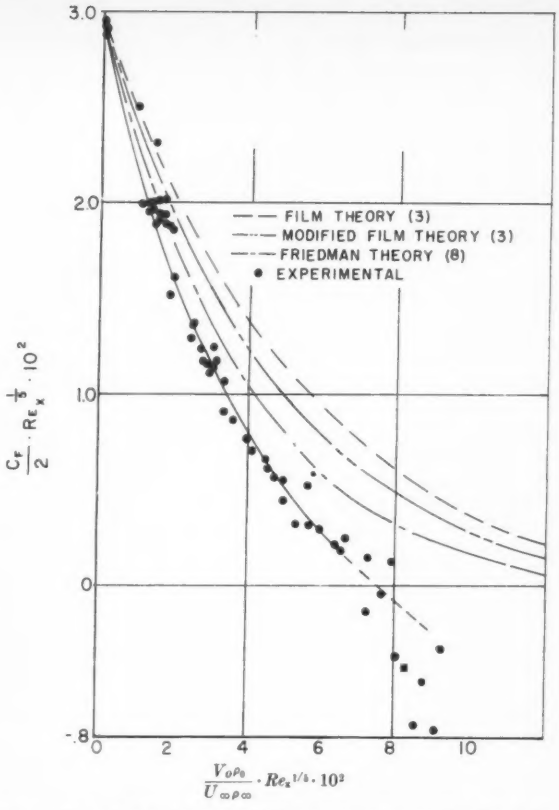

Fig. 1 Flat plate with mass addition constant properties $Eu = 0$; for air as both primary and secondary fluids

At present a more suitable description of the physical phenomena is being examined using methods similar to those of Townsend and Davies (6, 7) which may more precisely define the structure of the turbulent boundary layer with mass transfer.

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Interference During Burning in Air for Nine Stationary Fuel Droplets Arranged in a Body-Centered Cubic Lattice[1]

J. KANEVSKY[2]

Daniel and Florence Guggenheim Jet Propulsion Center, California Institute of Technology, Pasadena, Calif.

INTERFERENCE effects during burning in air for stationary body-centered cubic arrays of nine droplets have been determined for n-heptane and methyl alcohol by using a procedure similar to that described for two- and five-droplet arrays in a previous publication (1).[3] The burning rate of the droplet located at the center of the cubic lattice was measured for various lattice spacings and drop sizes. The square of the droplet diameter D^2 was observed to decrease linearly with time t, within the limits of experimental accuracy, for each of the burning droplets. However, the absolute value of the evaporation constant $K' = -d(D^2)/dt$ was found to be a sensitive function of droplet spacing, which also determined the flame shape. Since any finite spray can be approximated as a superposition of three-dimensional arrays, the results on interference during droplet burning suggest that (a) the relation $D^2 = D_0^2 - K't$, where D_0 is the initial droplet diameter, represents a phenomenologically acceptable description for spray combustion, and (b) the absolute value of K' depends not only on the physico-chemical properties of the fuel-oxidizer system but also on geometric factors affecting spray design.

Representative results for K' are listed in Table 1 for different droplet spacings. A representative plot of the observed values of D^2 as a function of time is shown in Fig. 1. Several of the runs showed a low-frequency, small-amplitude oscillation for D^2 about the values falling on the "best" straight lines. These oscillations were apparently produced by mechanical vibrations of the quartz fibers supporting the fuel droplets.

Table 1 Average values of evaporation constant K' for nine-droplet arrays of n-heptane and methyl alcohol burning in air

Fuel	Spacing of corner droplets (mm)	Average K' (cm²/sec)	No. of runs	Flame boundaries
n-heptane	9.5	0.0127	2	separate
n-heptane	8.5	0.0116	9	separate
n-heptane	7.5	0.0123	8	separate
n-heptane	5.8	0.0128	10	partially merged
n-heptane	3.6	0.0077	7	completely merged
Methyl alcohol	8.5	0.0104	1	separate
Methyl alcohol	7.5	0.0109	7	separate
Methyl alcohol	5.8	0.0108	7	partially merged
Methyl alcohol	3.6	0.00637	7	completely merged

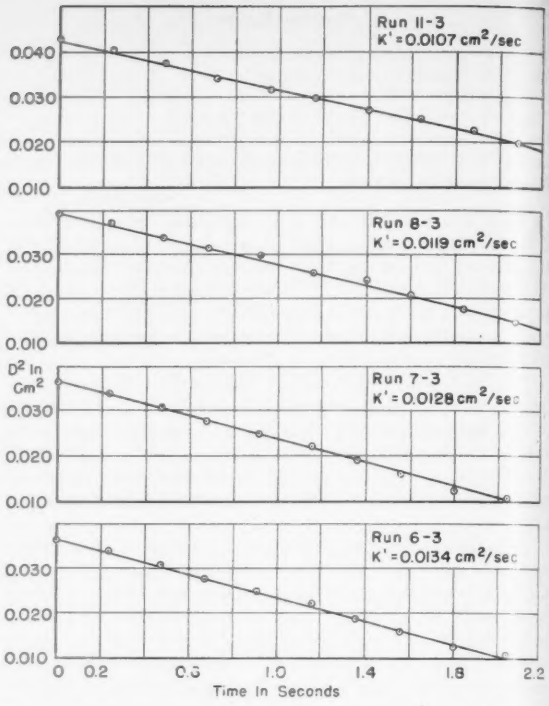

Fig. 1 Variation of D^2 with time for center droplet in 9-droplet, 3-dimensional array with n-heptane as fuel and cube edge spacing of 7.5 mm

Reference to the data given in Table 1 shows that, for the case in which the droplets are in close proximity and the flames are completely merged, K' is reduced by about 40 per cent below the value obtained for minimum interference. This decrease provides positive evidence for the practical importance of locally fuel-rich zones on burning rates.

The present results indicate that an analytical treatment of spray combustion, of the type first worked out by Probert (2), should be useful for a description of over-all burning rate provided an appropriate average value can be determined for the evaporation constant K'.

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Received June 15, 1956.

[1] Supported by the U. S. Office of Ordnance Research under Contract DA 04-495-Ord-446. Details concerning this work may be found in a thesis submitted to the Graduate School of the California Institute of Technology by J. Kanevsky, in partial fulfillment of requirements for the degree of Aeronautical Engineer, June 1956.

[2] Lt., U. S. Navy. Graduate student in Aeronautical Engineering (Jet Propulsion Option), 1955–56. The author is indebted to Dr. S. S. Penner, under whose direction the present investigations were carried out, for helpful suggestions.

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Medical Problems in Space Flight

(*Continued from page 756*)

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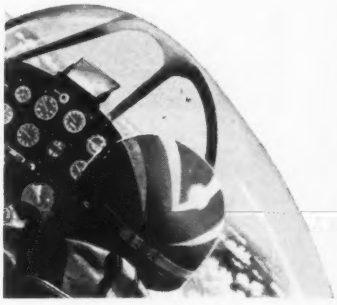

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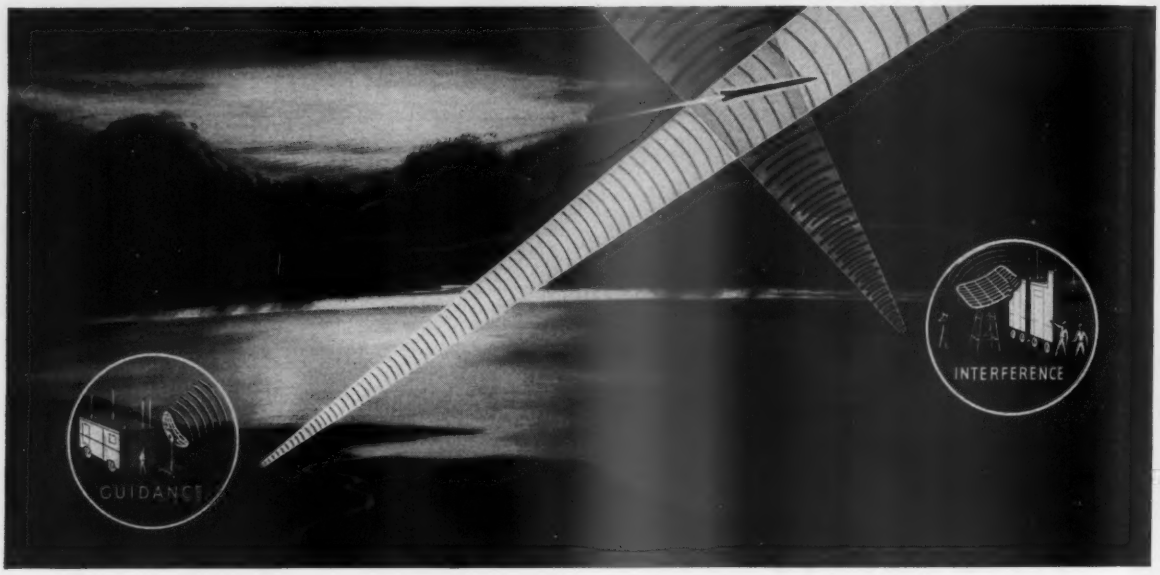

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What's in a Name?

TO FIND a name for its planned new Atlas facility, Convair Div. of General Dynamics Corp. (San Diego, Calif.) reached into the realm of space travel, came up with Convair-Astronautics.

Astronautics, the company says, was selected as the name most representative of the future products with which the new organization will be working. The facility will be devoted to research, development, manufacturing, and preliminary testing of the Atlas intercontinental ballistic missile, as well as related projects looking into the future of astronautics.

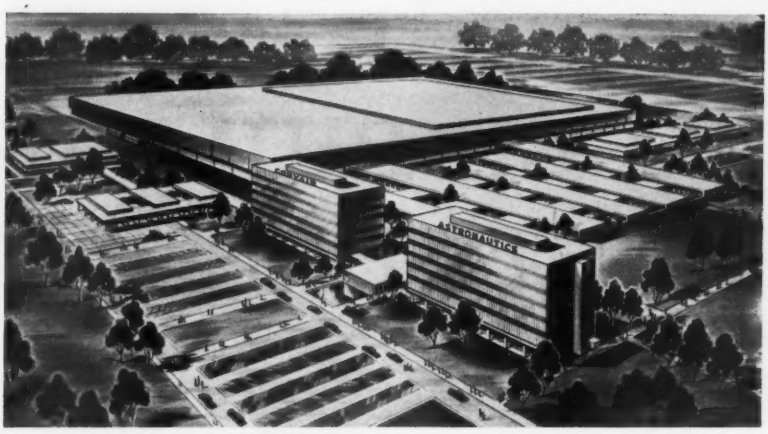
At this stage, there are no specific projects dealing with astronautics in the works. But Convair has "hopes," points out that it wouldn't spend $40 million on such an elaborate facility for the Atlas alone.

On a Mesa: Convair-Astronautics will be located on a 252-acre site on Kearny Mesa, approximately eight miles northeast of San Diego. The plant will consist of a one-story high-bay factory building of approximately 500,000 sq ft, two six-story office buildings of about 107,000 sq ft each, a 147,400 sq ft engineering laboratory, a cafeteria-auditorium, a 75,000 sq ft instrument and computer center, and several other buildings, totaling in all about 1 million sq ft of floor space.

The new facilities are being planned to provide for extensive research in the physical sciences, ultimately will house the laboratories and offices of Convair's new Department of Scientific Research, headed by Charles R. Critchfield.

With the exception of special equipment and machine tools paid for by the U.S.A.F., cost of the new facility will be borne by Convair, says Convair President Joseph T. McNarney.

The plant is scheduled for completion in the fall of 1957, is expected to be ready for partial occupancy by next spring. Until then, says J. R. Dempsey, director of the Atlas program, work on the Atlas will continue at Convair's San Diego Plant 1.



Convair-Astronautics plans $40 million plant for Atlas ICBM and "future" products

MISSILES

• As a preliminary to its participation in the United States Program for the International Geophysical Year 1957–1958, the Navy recently launched 10 balloon-supported rockets (Rockoons) from the USS Colonial (LSD-18) 200–400 miles west of San Diego, Calif.

Deacon solid propellant rockets were used in the tests. Made by Allegany Ballistic Laboratory (Cumberland, Md.), the rockets measure 12 ft from tip to tail, carry a 20-lb instrument payload.

Primary purpose of the tests, which were conducted under the direction of Herbert Friedman of the Naval Research Laboratory, was to investigate the effect of solar disturbances, including solar flares, on the electromagnetic radiations from the sun which, in turn, affect radio communications.

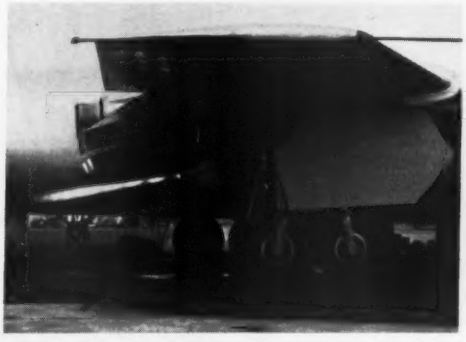
• A Ryan KDA Firebee target drone set a long range record recently at the Naval Air Missile Test Center (Point Mugu, Calif.). Powered by a Fairchild J-44 engine, the drone flew 210 miles at speeds greater than 600 mph.

At the same time, Ryan disclosed that it has received an Air Force contract for an advanced model drone. Designated XQ-2B, the new Firebee will be powered by a Fairchild FT-101 midget jet engine, a commercial version of the better known J-44. The drone will be capable of operating above 50,000 ft at high subsonic speeds. Use of

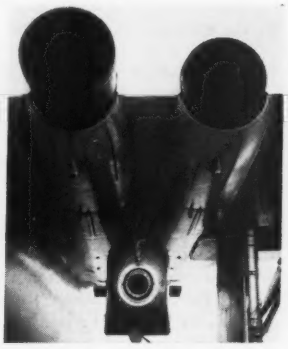
Sprite Takes to the Air

First British liquid propellent rocket engine to pass an official type-approval test in England, the de Havilland Super Sprite ATO unit was put on full display and freed of most security restrictions last year (see JET PROPULSION, March 1956, p. 193). But it was just recently that British authorities revealed that the Sprite was being developed specifically for the Vickers Valiant jet bomber.

Note in close-up external stiffeners riveted to Valiant tailpipes. In the interests of an aerodynamically clean craft, jettisonable nacelle takes all attachments and bracings except release mechanism with it on leaving the aircraft.



SIDE view shows mounting and firing angle. Secured by standard bomb-release mechanism, unit can be jettisoned, recovered by parachute



REAR close-up of Sprite discharge nozzle shows mounting between main engine cowlings

NEW THIOKOL ROCKET MOTOR PLANT TO BE BUILT IN NORTHERN UTAH

12,000-acre plant site acquired for rocket motor development center

Near the north shore of Utah's Great Salt Lake a new Thiokol plant will soon rise. This latest expansion by the Thiokol Chemical Corporation will bring to four the total number of Thiokol plants devoted exclusively to the development and production of solid propellant rocket motors.

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Thiokol chose this location in order to service the growing missile and rocket industry in the West. It will become Thiokol's western center for all guided missile engines and rocket motor development and production.

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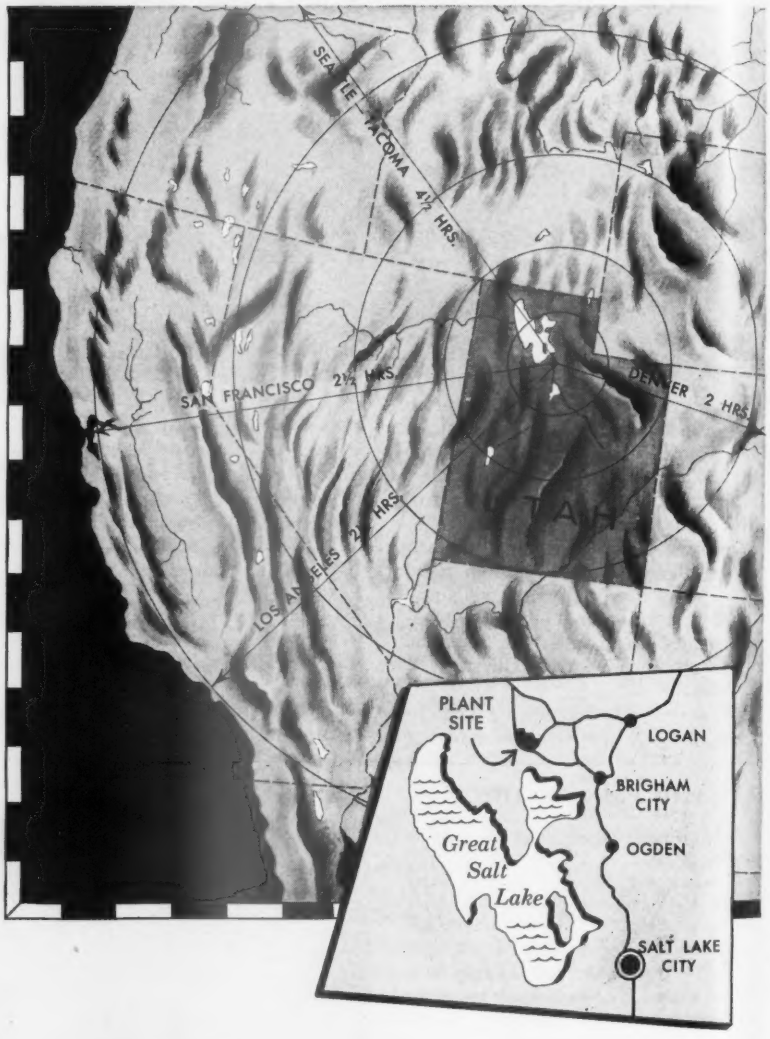

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special devices for radar reflectivity will enable the drone to create an "image" of a full scale plane for target purposes on tracking radar screens (see photos).

• Lieutenant Colonel Frank K. Everest, Jr., aboard the Bell X-2 rocket plane, scratched a record 1900 mph into the flight books, bettered Major Chuck Yeager's 1953 mark by 250 mph. The flight, revealed last month at the Air Force Association's New Orleans convention, took place in late July at Edwards Air Force Base.

• The Strategic Air Command has revealed plans for a strategic missiles squadron that will be ready to handle long-range guided missiles (IRBM and ICBM) "when they become operational."

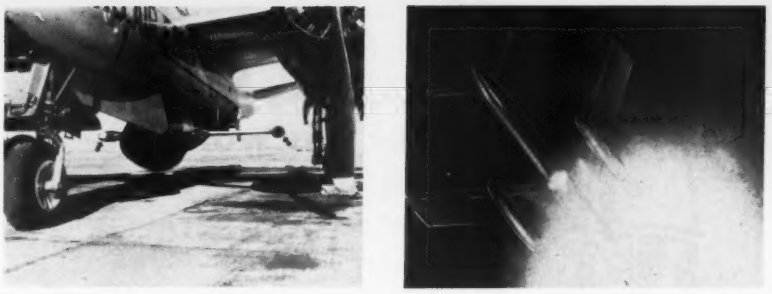
• Launching of IRBM's from submarines and surface ships 100 miles offshore will enable the U. S. to deliver atomic warheads on targets almost anywhere in Russia, say Navy officials. At the same time, warns the Navy, Russia, particularly with its vast underseas fleet, can be expected to develop the same potential in regard to U. S. targets.

• U. S. scientists have asked for the cooperation of Latin-American Governments in tracking the earth satellites to be launched next year. In particular, the U. S. wants to establish optical observation stations and radio tracking stations in a number of Central and South American countries.

• First production contract for Regulus II was awarded by the Navy to Chance Vought Aircraft, Inc. (Dallas). Worth $12 million, contract calls for construction of an air-breathing missile similar to Regulus I but bigger, faster, and with a longer range. (Regulus I has a range of about 500 miles and a speed about that of sound.) Ships now equipped to handle Regulus I will also be able to handle the new missiles.

The Navy now has 10 ships—four cruisers, four aircraft carriers, and two submarines—able to handle the Regulus I and a number of other ships armed with missiles, such as the Terrier. By 1961, the Navy predicts it will have 47 guided missile ships in all—enough to protect three carrier task groups. Included among these will be ships armed with Talos and Jupiter missiles which will eventually join the fleet.

• Earth satellites will be made of magnesium. Brooks & Perkins, Inc. (Detroit), a magnesium fabricating concern, has received a Navy contract to build the vehicles. Thirty-five satellites of two sizes—6-in. and 12-in. diam—are to be made for launching during the upcoming IGY program.

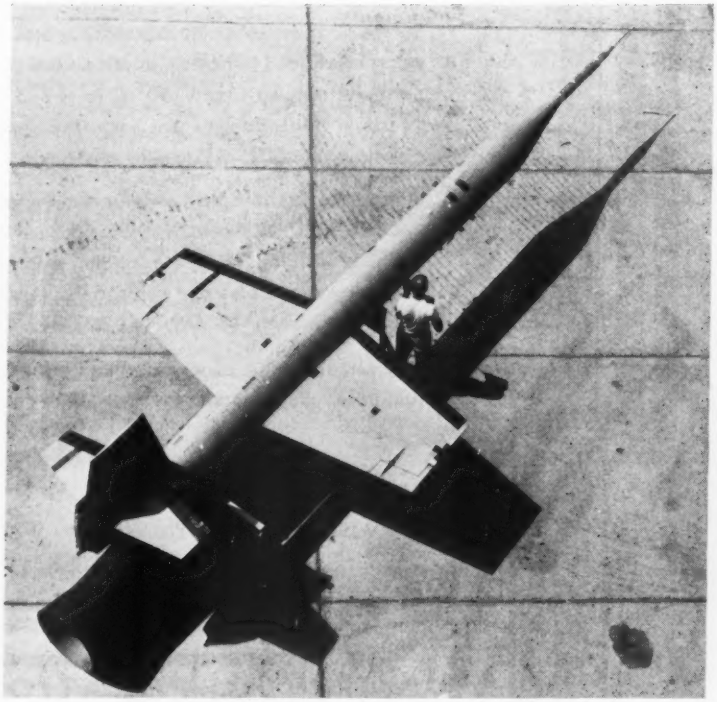


BIGGER THAN LIFE: Corner radar reflectors mounted in Fiberglas wing tip pods (see arrows, left) on Ryan Q-2A Firebee create radar "image" (right) of full-scale airplane

Earlier, Glenn L. Martin Co. (Baltimore), prime contractor for Project Vanguard, awarded a subcontract to Atlantic Research Corp. (Alexandria, Va.) to provide small solid propellant rockets that will be used as power units to spin-stabilize the third stage of the satellite launching vehicle and to separate the burnt-out second stage rocket shell from the third stage assembly.

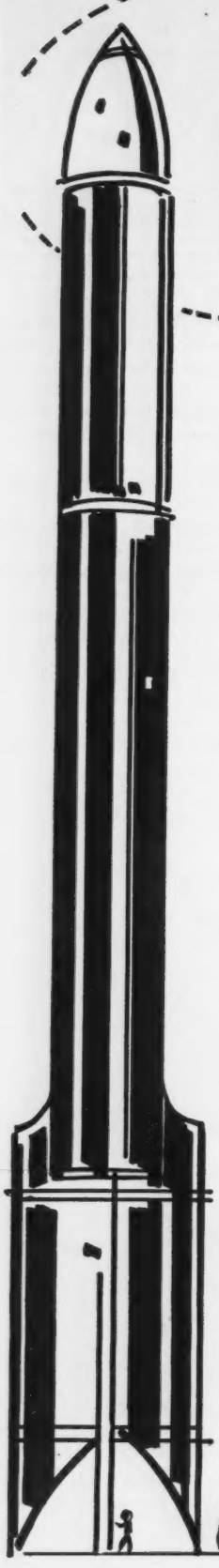
• Jupiter, an artillery-type intermediate range (1500 mile) ballistic missile, will be produced by Chrysler Corp. under a $3,175,000 engineering and production contract recently awarded by the government. The missile is designed to serve as a ground-launched weapon for the Army. In Navy use, it will be launched from both surface ships and submarines. Chrysler will continue production of the shorter-range Redstone which served as a basis for development of the Jupiter.

• Air Research Development Command's 5000-mile missile test range will be instrumented with magnetic tape recorders by Consolidated Electrodynamics Corp. (Pasadena) under a $1,200,000 Air Force contract. Extending southeasterly from Patrick AFB (Fla.) across the Atlantic to Ascension Island, the range will be used to test U.S.A.F. Intercontinental Ballistic Missiles.



Flying Laboratory for Ramjets

Last month, after several years' secrecy, the Air Force took the wraps off the Lockheed X-7. Launched from a B-29 and recovered by parachute, the supersonic X-7 is used to flight test new engines for U.S.A.F. ramjet missiles



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AIRCRAFT

• Latest aircraft in Republic Aviation's famed "Thunder" series is the F-105 Thunderchief, now entering production at Republic's Farmingdale, N. Y., plant. Capable of carrying nuclear weapons, the supersonic fighter-bomber is powered by a turbojet engine air-fed through wing-root intake ducts. The Thunderchief has short, very thin, swept-back wings and a long cylindrical fuselage. Set low on the aft section of the fuselage is a one-piece flying tail (stabilator); on the underside is a ventral fin designed to provide lateral stability.

• Kaman Aircraft Corp.'s (Bloomfield, Conn.) HOK-1 helicopter has been selected by U.S.A.F. to serve as a test bed for the first flight tests of the Lycoming XT-53 helicopter gas turbine (see photo). A "free" turbine, the XT-53 offers significantly lower weight and simpler operation than most other helicopter powerplants.

• Making a bid to put the first turbojet transports into commercial operation in the U. S., Capital Airlines placed an order for 14 de Havilland Comet IV's, expects first delivery in Nov. 1958.

• T2J is the designation of the new Navy jet trainer now under development by North American. Designed to operate from aircraft carriers, the trainer will be powered by J-34 turbojet engine, have a top speed above 400 knots, stall speed of 65 knots, and a ceiling above 40,000 ft.

• Radio Corp. of America is producing a compact, lightweight, electronic fire-control radar system for Lockheed's new F-104 Starfighter.

• The second, 600-mph, multi-jet Martin XP6M-1 Seamaster is now undergoing flight tests at Chesapeake Bay, Md. Crash of the first Seamaster was due to malfunction of control system. The condition, says the Navy, has now been corrected.

• Douglas F5D Skylancer, new all-weather, supersonic, carrier-based jet fighter, recently made its first flight. Similar in general appearance and arrangement to the F4D Skyray, the F5D is much faster. Powered by a J-57 turbojet engine with afterburner, the plane exceeded the speed of sound on its maiden flight at Edwards AFB.

• Army has awarded a $700,000 contract to Ryan Aeronautical Co. (San Diego) for the design and development of a flying test bed, "deflected slipstream," turbine-powered, VTOL aircraft.

• Navy has placed a $20-million production order with Chance Vought Aircraft, Inc. (Dallas), for F8U-1 Crusader jet fighters.

• Piasecki Aircraft Corp. (Philadelphia) is building under Navy contract an experimental, vertical lift aeronautical development. Nicknamed Sea Bat, the craft will be unmanned and completely automatic in flight. Small enough to be stowed aboard submarines, the Bat will be controlled electronically from shipboard.

• Vertol Aircraft Corp. (Morton, Pa.) has received a $850,000 contract from the Army for the design and development of a flying test bed, "tilt wing" turbine-powered VTOL aircraft.

• Martin Co. (Baltimore) will develop a new tactical bomber for the Air Force.

• Sperry Gyroscope Co. (New York) will deliver the first SP-30 electronic flight control systems specially designed for the DC-8 jet airliners to Douglas Aircraft Co. in the fall.

GOVERNMENT

• Speaking at the Air Force Association Convention in New Orleans last month, Brigadier General Don R. Ostrander identified Ramo-Wooldridge Corp. (Los Angeles) as the engineering and scientific supervisors of the Air Force Ballistic Missile Program which is presently concerned with development of the Atlas and Titan ICBM's and the Thor IRBM.

• Ever wonder what Air Force boys were talking about when they seemed to be walking a verbal "cloud deck"? Well, U.S.A.F. has just published The United States Air Force Dictionary to let laymen in on the special language of the "birdmen."

• At Germany's Berlin International Exposition, Sept. 15–30, U. S. Information Agency will stage an "air and space show" featuring a model of the earth satellite which the U. S. plans to launch next year.

• Positions for aeronautical research scientists with the National Advisory Committee for Aeronautics are still open. Salaries range from $4480 to $14,800/year. Applications (Forms 57, 58) may be obtained at any first- or second-class post office or from regional Civil Service offices.

• Ordnance Corps' Ballistic Research Laboratories (Aberdeen Proving Ground, Md.) are also looking for

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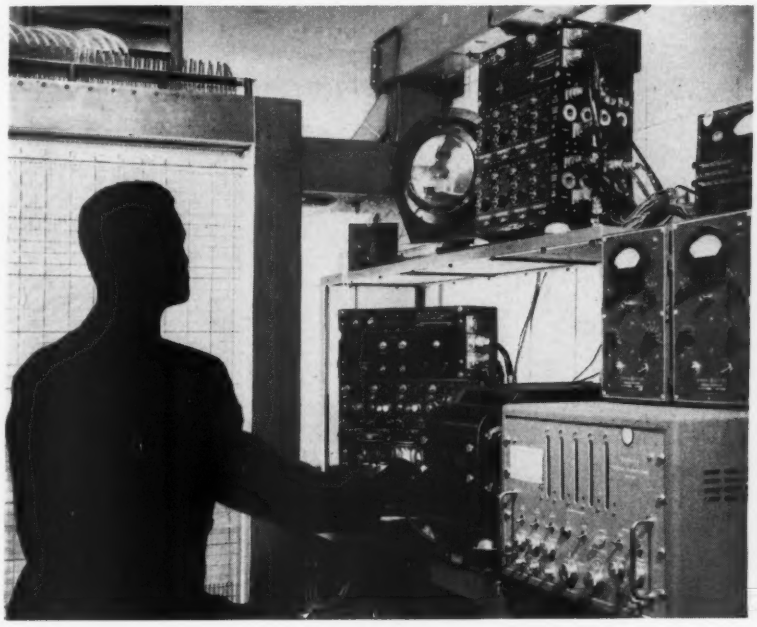

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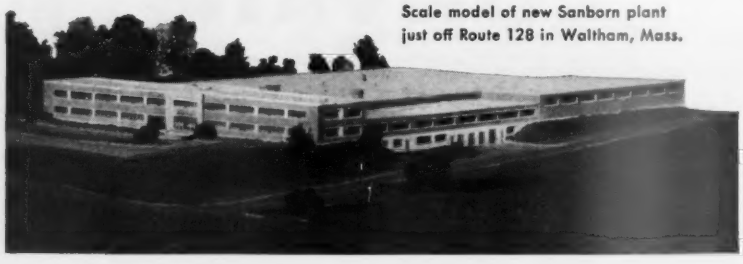
Completion of the structure late this year will mean vastly improved facilities for research, manufacturing and other operations. This will directly and immediately benefit not only the work Sanborn does, but also the people who use Sanborn systems, amplifiers, recorders and other components. It will make possible more rapid development and production of new instruments, and increased opportunity for a larger number of people to apply their skills to the problems of modern instrument design and manufacture.

This represents not "just a new plant", but a reflection of Sanborn's growing role in providing better answers to industry's oscillographic recording needs.

Sanborn Company, Industrial Division, Cambridge 39, Mass.



Scale model of new Sanborn plant just off Route 128 in Waltham, Mass.

people to fill positions in the upper atmosphere rocket research program at Fort Churchill, Canada. Additional information may be obtained by writing to L. A. Delasso, Chief, Ballistic Measurements Laboratory.

• Marking a decade of guided missile activity, the Army's Antiaircraft Artillery and Guided Missile Center at Fort Bliss, Texas, recently celebrated its 10th anniversary. Providing the nation with antiaircraft specialists, the center is in large measure responsible for the rings of Nike batteries over the U. S.

• Office of Naval Research is sponsoring a symposium on the "Technology of Molybdenum and Molybdenum-Based Alloys" to be held Sept. 18–19 at Rackham Memorial Building, Detroit. Attendance is by invitation only.

• Navy will establish a target drone and guided missile facility at Bonham Air Force Base, Barking Sands, Kauai, T.H. Drones will be flown from the facility to Navy exercise areas at sea to be used as targets; some missiles will be launched from ships and flown to Bonham for landing. Estimated cost of the facility is $500,000.

COMPANIES

• Following the example of companies such as Lockheed, North American Aviation, Glenn L. Martin, and Hawker Aircraft, Aerojet-General Corp. is getting into the nuclear energy field. To be known as Aerojet-General Nucleonics, the new subsidiary will develop and produce nuclear reactors.

• Lear, Inc. (Grand Rapids, Mich.) has received a $1,692,641 follow-up order on its original Air Force contract for automatic flight control systems to be installed in Boeing KC-135 jet tankers.

• Stressing the role of acoustical engineering in the new commercial jet age, Douglas Aircraft Co., Inc. (Santa Monica, Calif.), has formed a completely separate Acoustics Section.

• Air Research and Development Command has awarded Aerojet-General Corp. (Azusa, Calif.) a $133,-936 contract for research on ultra-energy fuels for rocket propellants.

• Bringing Fairchild Engine & Airplane Corp.'s (Hagerstown, Md.) backlog to over $200 million, new orders totaling $90 million recently received by the company call for new planes, engine and parts equipment. Among other projects, FED is currently developing a new, small, lightweight jet engine for U.S.A.F.

• U.S.A.F. and Boeing contracts totaling $2,600,000 with Solar Aircraft Co. (San Diego, Calif.) for gas turbine

engines and installation kits bring Solar's gas turbine bookings to more than $10 million since May 1.

• Piasecki Aircraft Corp. (Philadelphia) has received an Army contract to design, manufacture, and flight test a new, low cost, low maintenance helicopter rotor.

• Douglas Aircraft Co., Inc., is considering property in the Sacramento (Calif.) area as a site for its new missile test facility.

• Stauffer Chemical Co. is planning a tenfold expansion of its Niagara Falls facilities for the manufacture of boron trichloride—an important base in the manufacture of high energy fuels.

• Also at Niagara Falls, Olin Mathieson Chemical Corp. is planning to build a $36 million high energy fuel plant for the Air Force, a smaller plant for the Navy. The fuel, officially identified only as "Zip," is reported to be an alkyl borane(s). Thus, there could be a chemical tie-in between Stauffer and OM.

• The board of directors of Reaction Motors, Inc. (Denville, N. J.), has elected William C. Foster chairman of the board.

• General Dynamics has voted a 3-for-2 split of its common stock to holders of record at the close of business October 10, 1956.

• Pratt & Whitney Aircraft (East Hartford, Conn.) plans to add 3000 new employees before the end of the year.

• A new corporation, Thermo Materials, Inc. (Menlo Park, Calif.), will specialize in the development and production of precision high temperature ceramics.

• General Dynamics Corp. (New York) has received a $2,500,000 contract from the Army Corp of Engineers to design and build controls for the U.S.A.F. Arnold Engineering Development Center's new supersonic wind tunnel at Tullahoma, Tenn.

• Sperry Rand Corp. has formed a new Semiconductor Div. at Norwalk, Conn.

• Brooks & Perkins, Inc. (Detroit), specialists in the hot working of metals, last month opened its West Coast Engineering Div. in North Hollywood to service missile and aircraft producers working with magnesium and titanium.

INSTITUTIONS

• Ten Daniel and Florence Guggenheim fellowships were recently awarded to outstanding students chosen for their technical ability, leadership qualities, and interest in the fields of flight structures, rockets,

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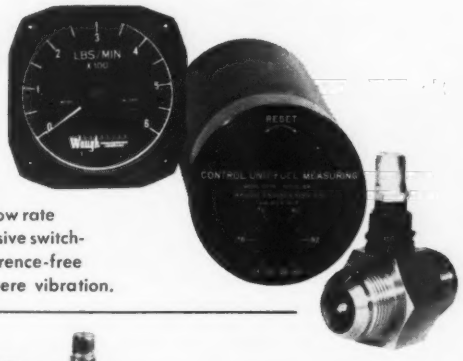

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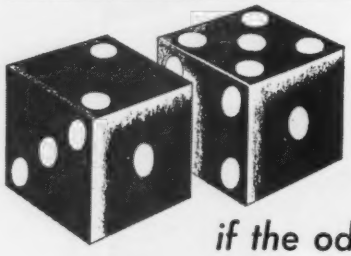

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and jet propulsion. The one-year grants consisting of tuition and stipends ranging from $1200 to $2000 to cover graduate study at the Daniel and Florence Guggenheim Institute of Flight Structures at Columbia and the Guggenheim Jet Propulsion Centers at Princeton and California Institute of Technology went to the following:

Columbia—Irving W. Jones, Washington, D. C.; Leonard C. Lidstrom, Lexington Park, Md.; John M. McCormick, Jr., Philadelphia; Charles W. Miller, Niagara Falls, N. Y.; Enrico A. Patrone, Elmont, N. Y.

Princeton—Henrik J. Hagerup, Cambridge, Mass.; Arthur Sherman, Cincinnati; Martin Sichel, Albany, N. Y.

Caltech—Gunnar E. Broman, Stockholm, Sweden; Allen E. Fuhs, Pasadena, Calif.

• Northrop Aircraft, Inc. (Hawthorne, Calif.) has established a work-study fellowship program in cooperation with the University of California at Los Angeles to encourage advanced training for future engineers.

• Lear Foundation, Inc. (Grand Rapids, Mich.), has established an engineering scholarship grant at University of Michigan with the suggestion that it be used to further the education of a student majoring in aeronautical engineering or specializing in electronics as applied to the aircraft industry.

• The Advisory Committee on Science Manpower, appointed by the New York City Board of Education, may recommend employment of retired scientists and engineers to meet the present shortage of science and math teachers.

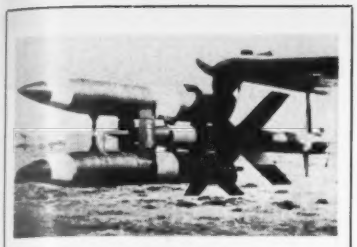
FOREIGN

England: New details of A. V. Roe & Co., Ltd.'s (Woodford, England), proposed supersonic wind tunnel have been released. The tunnel will cost $280,000, have a working section 27 in. by 30 in., provide speeds ranging from Mach 1.5 to 3.5 in runs up to one minute. The tunnel will be used for preliminary design and development testing.

• Hawker Siddeley turbojet Gloster Javelin fighters are now in operation with the RAF.

• Two new versions of the Gloster Meteor fighter, Meteor U.15 and U.16, will be used as target drones for guided missiles.

• Britain is building a new research rocket for the forthcoming IGY program. Designated the Raven, it will be a 1-ton vehicle designed to climb 100 miles in $2^1/_2$ min.



Clustered Destruction

Now in production for the RAF, Fairey Fireflashes are first British air-to-air guided missiles designed to destroy radio-controlled planes. Propelled to supersonic speeds by solid fuel rockets, missiles carry a warhead which explodes as soon as it is within lethal range of the target

• Also in connection with the IGY program, Bristol Aircraft, Ltd., is making solid propellant motors to power British high altitude rockets. Designed to carry 100 lb of instruments to heights of 120 miles, the rockets will be 25 ft long. Burning time will be 25 sec.

Canada: Canadian Steel Improvement, Ltd., has developed a new process for forging titanium which reportedly eliminates many production problems and cuts costs.

Japan: Japan's National Defense Agency will import 400 Swiss Oerlikon air-to-air missiles as the first step in its newly authorized air-to-air missile research program.

France: The first American ejection seat system to be used in a European jet will be one designed by Republic Aircraft's Escape Systems Group. It will go into the new Dassault Mystere IV fighter.

• Another Dassault craft, the Super Mystere B.2, exceeded the speed of sound in its first flight without using its afterburner. The craft is powered by an Atar 101G turbojet.

RESEARCH & DEVELOPMENT

• Sperry Rand Corp. has selected Salt Lake City, Utah, as the site of its new $1,250,000 research and development facility which will play an important role in its weapons program for the armed services.

• Raytheon Manufacturing Co. has purchased a 15-acre site in Goleta, Calif., for its new engineering laboratory to be used in the design and development of airborne electronics and infrared equipment.

• Fairchild Camera and Instrument Corp. (New York) has received a $52,000 contract from Wright Air Development Command's Aerial Reconnaissance Lab for the design of an airborne 35-mm film processing machine.

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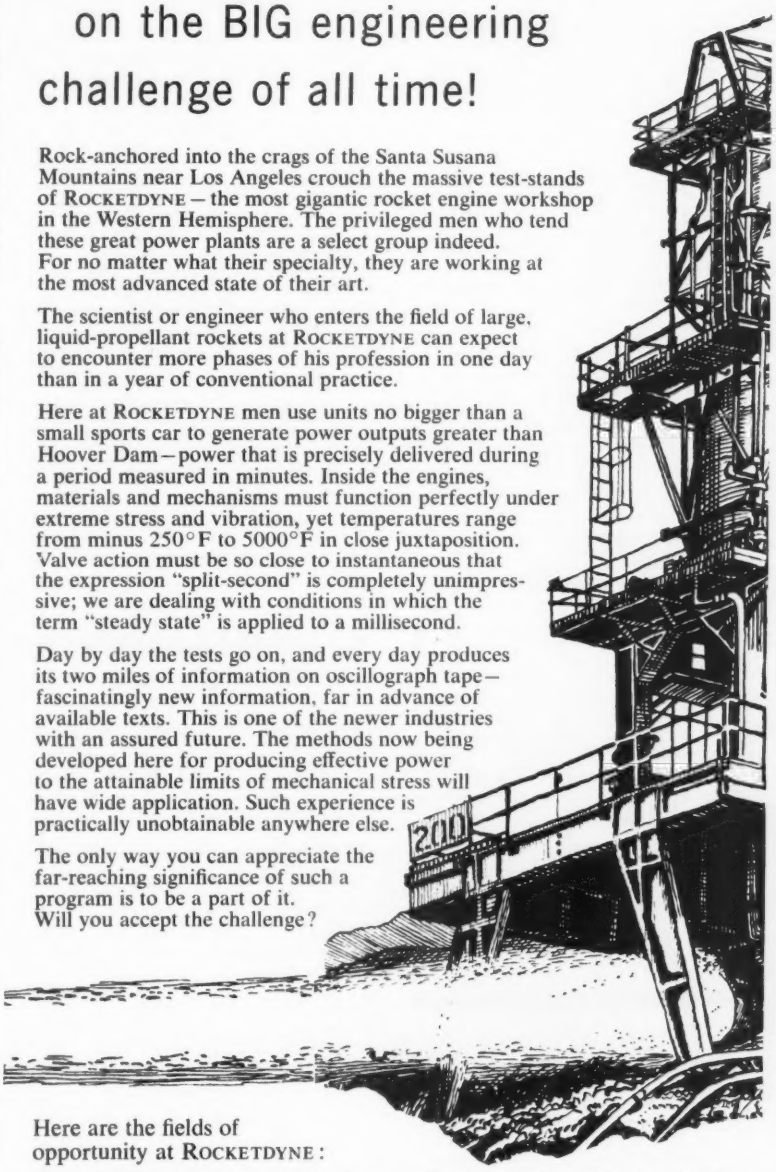
Day by day the tests go on, and every day produces its two miles of information on oscillograph tape – fascinatingly new information, far in advance of available texts. This is one of the newer industries with an assured future. The methods now being developed here for producing effective power to the attainable limits of mechanical stress will have wide application. Such experience is practically unobtainable anywhere else.

The only way you can appreciate the far-reaching significance of such a program is to be a part of it. Will you accept the challenge?



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First in Controls

• From the Air Force, a $4,393,473 contract to Minneapolis-Honeywell for additional MB-1 automatic pilot systems for McDonnell's F-101A Voo-Doo supersonic fighter.

• Wright ADC has awarded Fairchild Camera and Instrument Corp. a development contract for three prototype models of a rocket scoring camera to be used for air-to-air rocket training.

• Also from Wright ADC, a $250,000 study contract to Aeronautical Div. of Minneapolis-Honeywell Regulator Co. for research engineering in the field of turbojet inlet diffuser control.

• Southwest Research Institute (San Antonio, Tex.) is building a $600,000 "hot lab" for Pratt & Whitney as part of the latter's nuclear powered aircraft program.

• McDonnell Aircraft Corp. (St. Louis) has established a Research Dept. to supplement and contribute to the work of its Airplane, Helicopter, and Missile Engineering Divisions.

• U.S.A.F. has contracted Armour Research Foundation of Illinois Institute of Technology (Chicago) to develop a method to suppress visible jet vapor tracks.

• Research Div. of Marquardt Aircraft Co. (Van Nuys, Calif.) has moved into the first unit of the new Marquardt Research Center.

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Selection of Engineering Training in the Field of Rockets, Jet Propulsion, and Astronautics

GEORGE P. SUTTON,[1]

Rocketdyne, A Division of North American Aviation, Inc., Canoga Park, Calif.

Three questions most frequently asked by students interested in the field of rockets, jet propulsion, and astronautics are presented. A discussion is made of the number and complexities of specialties in a field such as rocketry. The objectives of an engineering education are presented, and the curriculum recommendations of the Committee on Evaluation of Engineering Education analyzed. Aspects of graduate work and graduate schools as related to the field of rockets, jet propulsion, and astronautics are reviewed. Criteria for evaluation of an engineering school are detailed. It is concluded that a student should emphasize science and broad, general studies in his curriculum, that no decision on a specialty should be made until experience is gained as an engineer or scientist in the field, and that the selection of a school and its faculty is more important than the proper choice of a curriculum.

INTRODUCTION

OFFICERS of the AMERICAN ROCKET SOCIETY and practicing engineers in the field of rockets, jet propulsion, and astronautics report that three dominant inquiries are received from prospective college students:

1 In what field of engineering should a student specialize in order to prepare himself best for a future in rocketry, jet propulsion, or astronautics?

2 What elective courses should he choose to prepare himself for this career?

3 What factors should be considered in selecting an engineering school?

With these questions in mind a survey was conducted recently by the AMERICAN ROCKET SOCIETY to learn what academic training is being offered engineering graduates and undergraduates which will prepare them for work in jet propulsion, rockets, and astronautics. Questionnaires were sent to leading colleges and universities throughout the country. The results were evaluated and the information incorporated in the following discussion. The opinions expressed here are those of the author and do not represent the views of the AMERICAN ROCKET SOCIETY or North American Aviation, Inc. It is tacitly assumed that the student who asks these questions is fully qualified for entering upon a college course.

Received April 12, 1956.

[1] Chief, Preliminary Design Section. Director ARS.

FIELD OF SPECIALIZATION

Even in the realm of rockets, jet propulsion, and astronautics engineering there are many fields of specialization. The industry needs civil, mechanical, aeronautical, chemical, electrical, industrial, and petroleum engineers. It needs the services of such specialists as physicists, chemists, business administrators, economists, mathematicians, physical chemists, and metallurgists. To a large extent, choice of a specialty will depend upon the temperament, preference, and abilities of the individual. Some engineers with a flair for structural visualization become designers; some with a liking for mathematics become analysts; and others gifted with creative inspiration make their contribution in pure research.

Some have the ability to learn and absorb quickly complex technical information which can then be put to use; others obtain satisfaction from the solution of analytical problems; still others derive pleasure by helping those about them. These are typical personal characteristics which should influence the choice of the specialty.

It is important, therefore, that the student recognize these limitations and traits and then match them with the various specialized opportunities. This requires an intimate knowledge of the potential specialties available in the chosen field. Specialties may be organized into three categories:

1 Specialization by enterprise. Includes private companies, government agencies, university laboratories, nonprofit research institutions, and foreign organizations.

2 Specialization by product. Includes propulsion, guided missiles, fuels, fire control equipment, instruments, telemetry, space travel, and stellar observation equipment.

3 Specialization by activity. Includes design, analysis, experimental and theoretical research, production liaison, planning, field service, testing, administration, sales, development.

It can be seen that specialties, even in a narrow field such as rocketry, are numerous, involved, and complex.

Seventy-five per cent of the prominent professors and engineers reached by the AMERICAN ROCKET SOCIETY survey recommend that a decision on the field of specialization should not be made before the senior year or until some time after graduation. Only a small portion felt that this decision should be made in the junior or sophomore year. The curriculum of the schools reflects this thinking. Only six per cent of all the schools surveyed recognize rockets or jet propulsion engineering as a major curriculum in the undergraduate schools. Ten per cent of the schools offer it at the graduate level. Over fifty per cent of the schools offer courses in jet propulsion engineering as an elective during the senior and graduate years.

Few of the people experienced in their profession today actually started out to train for this profession during their college years. Most of the recognized authorities in jet propulsion probably never heard of this particular opportunity in their student days. Twenty years from now, when our present student generation will be heading engineering departments in industry, they will look upon our rocket propulsion as an old, specialized art, as old as the World War I Liberty aircraft engine appears to us today.

It is difficult to predict the direction in which our future propulsion designs will grow. A general background well founded in the fundamentals of engineering and science is more likely to give the student a foundation in future areas of space flight than any specific set of courses, at best only elementary, offered in today's engineering schools.

It is significant that many industries and some government agencies train employees in the specialties. Today North American Aviation's Rocketdyne Division, for example, offers its engineering employees courses in the principles and elements of rocket propulsion devices. Many companies offer financial incentives for acquiring specialized or generalized training in evening courses.

CHOICE OF MAJOR

Some of the major curriculums, such as mechanical engineering, offer a broad basis for possible work in a variety of different fields. Others, such as astronomy or physical chemistry, are admittedly more specialized and narrower in their field. However, almost every type of technical endeavor is required in the development of a complex system, such as a satellite, and any one of a dozen different major courses will be a satisfactory preparation for employment in the

field of rockets, jet propulsion, or astronautics. This includes chemistry, physics, mathematics, chemical engineering, electrical engineering, civil engineering, mechanical engineering, optics, applied mechanics, metallurgy, operations research, astronomy, or aeronautical engineering. Once employed, there usually is opportunity to learn more and eventually become a true specialist, irrespective of the major option chosen in college.

The following is a major breakdown of the various types of 745 engineers in one engineering department at a large rocket manufacturer:

Mechanical engineers	32%
General engineers	4%
Aeronautical engineers	4%
Civil engineers	2%
Electrical engineers	8%
Physicists	5%
Chemical engineers	4%
Chemists	7%
Mathematicians	3%
Others	31%

Of the 745 engineers, 61 per cent have B.S. degrees, 10 per cent M.S. degrees, 3 per cent Ph.D. degrees, and 26 per cent have no degree. As a point of interest, there was even one marine engineer in the group.

Today there are some men who graduated as metallurgists in charge of a quality control department, chemical engineers running an aerodynamics engineering group, and graduate physicists as responsible senior mechanical designers. Although these switches from the major field in college to another field are not practiced regularly, they occur often enough to prove that choice of a major course in school is not the final choice of a technical specialty in the profession.

The selection of the major course of study should perhaps be influenced more by personal preferences, other interests, long-range objectives, and the temperamental character of the individual, rather than by the eventual field of specialization within the rocket industry.

OBJECTIVES OF ENGINEERING EDUCATION

There are two major objectives in engineering education, one technical, the other nontechnical. The technical goal is preparation for the performance of analysis and creative design or of construction, production, or operation in which a full knowledge of the analysis and design of the structure, machine, or process is demanded. This goal can best be achieved by schooling in fundamentals and basic sciences, and by the use of this scientific background in engineering analysis, in the study of engineering systems, and in the preparation of creative design.

The nontechnical goal envisions the developing of leadership qualities, the instilling of a deep sense of professional ethics, and a general humanizing and broadening of the student. Integral to this objective is the development of the ability to convey information to others correctly and concisely in a clear, logical, and interesting manner.

RECOMMENDED CURRICULUM

In a report by the Committee on Evaluation of Engineering Education, published in June 1955 by the American Society for Engineering Education, the recommendations listed in Table 1 were made.

The Committee emphasizes the value of engineering science, defined as the study of basic scientific principles as related to engineering problems and situations. The fields of engineering science specifically include: mechanics of solids (statics, dynamics, and strength of materials), fluid mechanics, thermodynamics, electrical theory (electrical circuits, field, and electronics), transfer and rate mechanisms (heat, mass, and momentum transfer), and the nature and properties of engineering materials.

Practicing engineers agree that mathematics and the basic sciences, such as chemistry and physics, including an introduction to nuclear physics, should be heavily emphasized by the student. Even more important are the basic principles of thermodynamics, fluid flow dynamics, and the special properties of materials as they depend on their internal structure. These courses in basic science encompass the solid, unshifting foundation upon which an engineering curriculum can be built with assurance and conviction.

Table 1 Recommended division of curriculum

Subjects	Approximate division
Humanistic and social studies	One-fifth
Mathematics and basic science	One-quarter
Engineering science	One-quarter
Major departmental sequence of analysis design and engineering systems including necessary technological background	One-quarter
Option or electives in	
a Humanistic-social	
b Basic science	
c Engineering science	
d Research or theses	
e Engineering analysis and design	
f Management	One-tenth

The Committee places least emphasis on specialized interdepartmental courses. Elective courses are believed to be more useful if they are broad and general. Finally, the Committee feels that for some, electives should be channeled to the building of a strictly humanistic and social background; for others, elective courses should be used to build a strong scientific background; and for all, electives should *not* be used for narrow courses within the field of specialization.

In his zeal for technical training the engineering student should not forget the importance of history, economics, government, literature, social philosophy, English, and fine arts. These should be utilized to achieve social understanding and a broad, humanistic background, as well as the ability of self-expression.

GRADUATE STUDY

Experience indicates a marked correlation between a student's undergraduate standing and his subsequent graduate performance. If an undergraduate stands in the upper quarter of his graduating class, it may be assumed that he is qualified for a master's program. If he is among the upper one-tenth of his graduating class, it may be assumed that the student will be a good doctoral risk. If the students of the colleges surveyed are taken as representative, the survey indicates that fifteen per cent continue to study for MS degrees. Only six per cent undertake doctorate studies in the fields generally related to rockets, jet propulsion, or astronautics.

In addition to high academic standing, the graduate student should also have a keen interest in research and advanced scientific principles. Many practicing engineers believe that graduate study should be offered only to qualified students.

A successful graduate program not only maintains high qualifications for its students, but also maintains a qualified faculty and adequate administrative and financial support. Even more than in undergraduate work, an understanding faculty is the most important requisite for a successful graduate school. Here teachers and students work closely in classroom, office, and laboratory. The graduate teacher must engage in creative research in order to be effective in the development of a student's ability to perform outstanding creative work.

Graduate study is usually accompanied by active research. This requires considerable financial support

in the form of scholarships, research grants, and research contracts with government or private industry. The availability of this financial and administrative support is an important factor in the selection of a suitable graduate school. The AMERICAN ROCKET SOCIETY survey indicates that a large percentage of schools offer scholarship opportunities for both graduate and undergraduate study in the fields generally related to rockets, jet propulsion, and astronautics.

CHOICE OF SCHOOL

An important factor in the creation of a good educational institution is a balanced and capable faculty. The faculty should include highly trained theoretical men with imagination and creative abilities and men of experience who have worked in the field and in industry, who have achieved professional and personal stature, and who possess seasoned judgment. The rapid progress of our technology makes it essential that faculty members maintain an active interest in the field by means of sabbatical leaves, summer work in industry, and consultation and government work. Almost without exception the colleges which reported to the survey indicated that their faculty members are given opportunities to participate in outside work.

A further indication of the capabilities of a faculty is the significant publications of its members and their production in research and in other creative areas, including new methods of presenting subject material to their students.

In the evaluation of a school, attention should be given its facilities, particularly its laboratories. Though this factor is believed to be less important than the quality of the faculty, it must be conceded that a school which frequently replaces its laboratory and machine shop equipment with new and more modern machinery is more desirable than one whose laboratory equipment is obsolete and inadequate.

The existence of a graduate school associated with an active research program for students and faculty is an important factor in comparing one engineering school with another. By engaging in advanced research work, the faculty stimulates its own creative work and is better able to present such material enthusiastically in the classroom. Of the eighteen techcal colinleges reporting in the survey, sixteen maintained a graduate school in addition to their undergraduate school. Thirteen had an active working relation with a nearby laboratory or a sponsored research project.

In selecting an engineering or science college the presence of technical student organizations on the campus affiliated with national science or engineering professional societies should be noted. These not only permit a forum for student expression but also enable lecturers and technicians from industry to present opinions and information helpful to students in choosing curriculum and specialties.

There were three to eight student societies in each of the schools surveyed. Only six schools had an active Section of the AMERICAN ROCKET SOCIETY on the campus.

One method for gaining insight into the activities of an engineering school is to hold open and frank discussions with people who have had experience with the school, its graduates, and its faculty. Personnel interviewers of the larger corporations have valuable opinions on the relative merits of different colleges. Probably the best source for an evaluation is the alumni. These men usually are able to indicate the strong and weak departments and, if they have achieved professional competence and maturity, can best evaluate the men on the faculty.

CONCLUSIONS

As a result of the survey conducted by the AMERICAN ROCKET SOCIETY, and of discussions and correspondence with engineers in the field, the following conclusions have been reached.

In his choice of curriculum, the student should emphasize science and basic engineering, together with broad general studies as opposed to practical and descriptive courses in engineering.

Fundamental understanding is the basis for a wide field of endeavor and is equally applicable for any specific engineering career. Practical "know how" changes with the times and rapidly becomes obsolete as new discoveries are made.

The student should not choose his detailed specialty until he has been working for some time as an engineer or scientist in the field. At that time he will have gained an insight into the structure of the organization and the engineering problems presented; he will have a better understanding of the opportunities offered in various specialties; and he will have achieved a better self-appraisal of his own personality traits and limitations.

The choice of a major, such as chemical engineering or physics, should not be influenced by eventual employment in the rocket industry but be guided by the interests, preferences, and personal characteristics of the student. Any one of a dozen different major curriculums will quality the student for employment in the field of jet propulsion, rockets, and astronautics.

Special consideration should be given by the young engineer to professional society membership, since this is a particularly important part of his continuing education. Professional society membership, both as a student and a young engineer, provides an opportunity for a man to gain additional first-hand experience, develop "know-how," make personal and professional contacts, and obtain an appreciation of the myriad problems of the rapidly developing rocket field.

The selection of a good school with a competent faculty is more important than the proper choice of a curriculum.

ACKNOWLEDGMENTS

The cooperation, help, suggestions, and support given to the author by Wernher von Braun, Richard G. Folsom, Richard W. Porter, and Noah S. Davis is gratefully acknowledged. These people not only took time to read the article and make comments, but they actually composed letters to students which contained ideas useful to this article.

NEW MISSILE RESEARCH CENTER

Lockheed's new Research Center at Stanford University's Industrial Park, Palo Alto, California, is the first step in a $20,000,000 expansion program—a program which has created new openings in virtually every field of endeavor related to the technology of missile systems and other forms of sophisticated flight. Please address inquiries to the Research and Engineering Staff at Sunnyvale.

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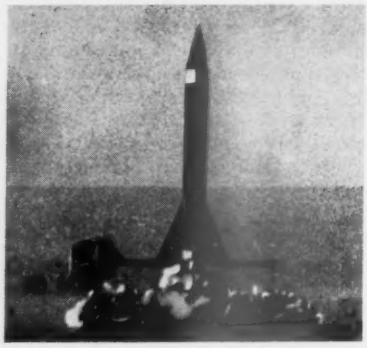
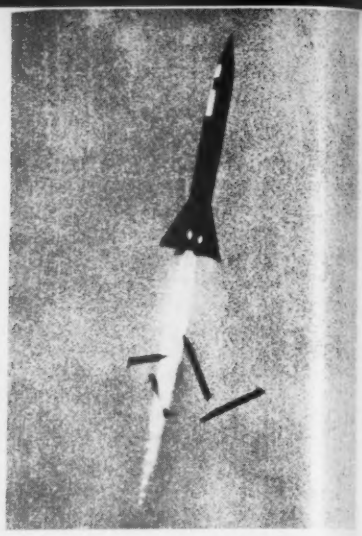
French Rockets and Missiles

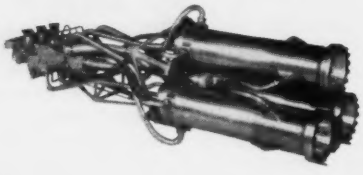
While their jet aircraft were catching the public's collective eye, French scientists and engineers, working with little fanfare, dug away at more fundamental studies. From this research has now come the foundation for France's rocket and missile program. Loaded with potential, the program already has a number of projects underway and others ready to roll. The vehicles themselves range from guided missiles to piloted aircraft, from rockets to pulsejets.

Here are just a few that you will be hearing more about:





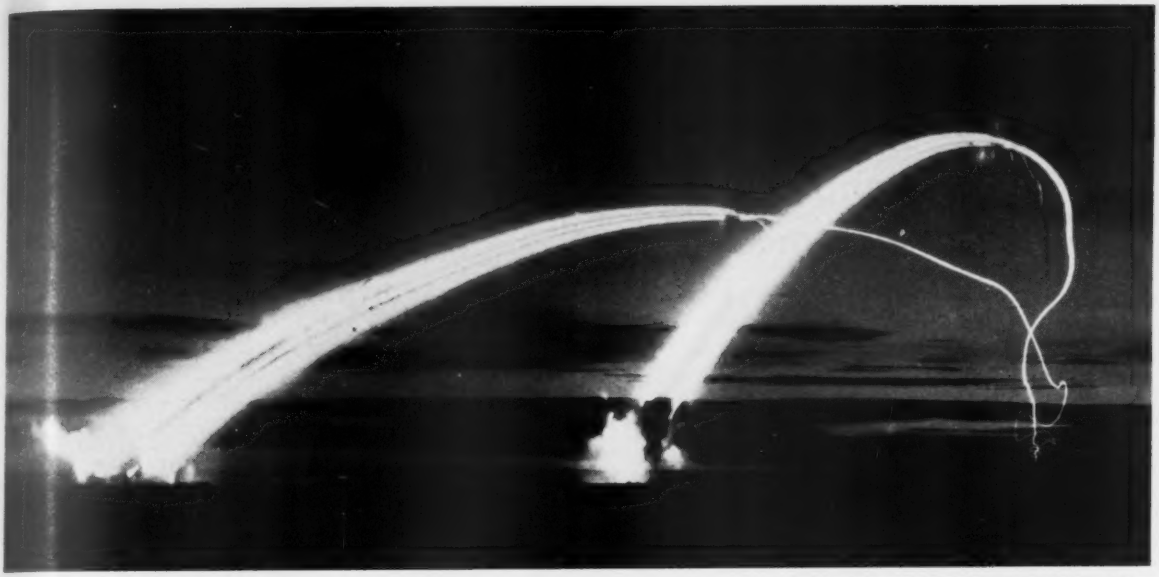
VERONIQUE TAKES OFF for trial run over North African desert. **A high altitude sounding rocket, vehicle recently reached 84 miles, is aiming for 137 miles. Four 180-ft cables attached to launching table (left) give rocket correct flight "tilt," are released along with outrigger arms (right) shortly after take-off. Veronique is powered by an 8800-lb thrust, nitric acid-diesel oil, regeneratively-cooled engine, is 24 ft long and 1.65 ft in diameter, weighs about 950 lb empty, and has 245-lb payload capacity.**



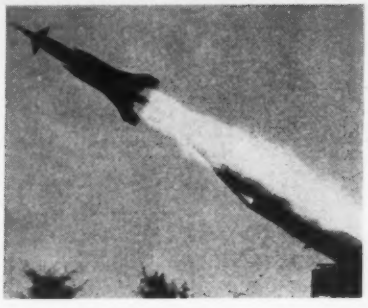
ROCKET POWER for Trident 9000 (right) comes from three-chambered SEPR 481 engine which burns a mixture of hypergolic furfuryl and nitric acid. With two wing-tip turbojets (for take-off) and three-barreled rocket engine, Trident can reach Mach 1.5 and stay aloft for 4½ minutes. Engine chambers operate separately or in unison, have total thrust of 9930 lb.

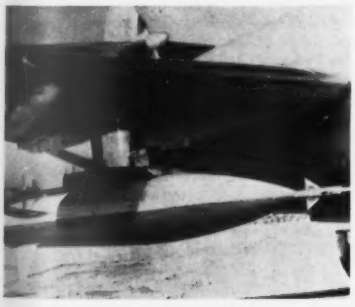
TAKE-OFF TRICKS are needed to get these two piloted aircraft airborne. SE 5000 Baroudeur (left) uses a launching trolley powered by two solid boosters, lands on skids. Leduc 021 ramjet (right) rides mother ship into the air. A new model, the 022, will be equipped with turbojets for take-off, a ramjet for flying. Designed to climb 80,000 ft in five minutes, Leduc 022 will fly at Mach 2, carry 600 gal fuel for 10-minute flight. A subsonic craft, Leduc 021 flies near Mach 0.9, climbs at 40,000 fpm.

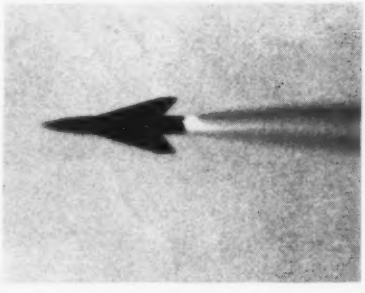
SUBSONIC TARGET MISSILES: ARS 5.501 (left), a reworked V-1, is powered by a pulsejet delivering 220-lb thrust. Speed is 280 mph; cruise height, 13,000 ft. Later model ARS 5510 (right) is powered by a turbojet of 880-lb thrust, flies at 560 mph, and cruises at 32,000 ft. Both missiles weigh about 1400 lb, are ramp-launched by two solid rockets.



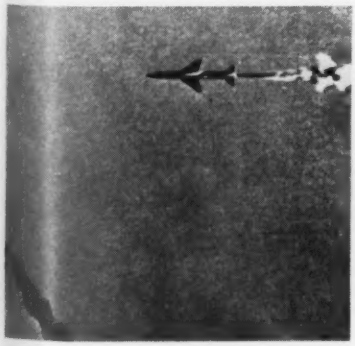
NIGHT FIRING of two unidentified SNCASE missiles at Cannes is shown above. Craft could be SE.4200 missiles which use solid booster rockets and a ramjet to reach 60-mile cruise range. Other new missiles, at right, are Jeep-mounted, wire-controlled "suitcase" SS-10 antitank rocket which weighs 33 lb and has a 1.3-mile range; and the experimental, 2000-lb PARCA (projectile autopropulse radioguid contre avion) AA missile, a multistage cluster rocket, which already has exceeded 60,000 ft in tests and is undergoing still further development.

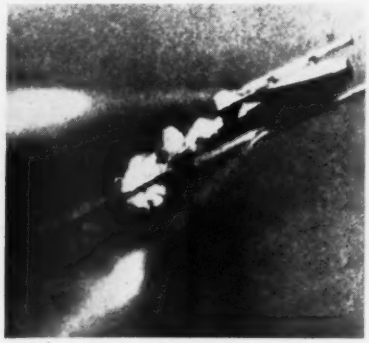


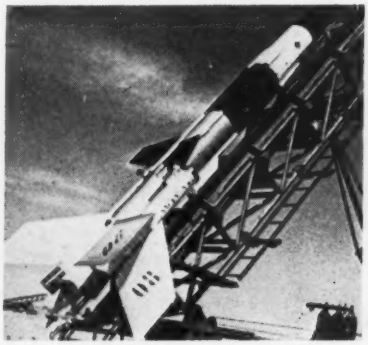




UNDER WING of Meteor fighter for test flight is the Matra R.051 (left) air-to-air missile which is about 10 ft long, 3.28 ft in diameter, and weighs 350 lb. Another air-to-air missile test-carried by the Meteor (center) is the two-stage solid propellant rocket, SPECMAS 5103 (right) which is 8.2 ft long 2.6 ft in diameter, and weighs 280 lb.







SHOOTING OVER SAHARA, two-stage Matra 04 (left) works out its kinks in North Africa along with other French test missiles such as SE.420 (center) and SNCAN 55.240 (right), a ramjet missile boosted by several large solid propellant rockets.

Radiation effects being studied in special laboratory

The flight date of the first atom-powered airplane may well be advanced as the result of a study being conducted by Admiral for the U.S. Air Force. The problem is to determine the effects of nuclear radiation on electronic components.

All types of electronic components . . . such as tubes, resistors, condensers, capacitors and coils . . . are first bombarded by neutrons to make them radioactive prior to observation and testing.

Admiral has equipped a special nucleonics laboratory to make this study. Test equipment is set up within heavily shielded "hot cells" and operated by remote controls outside each room. One of the "hot cells" contains environmental chambers for testing the radioactive components under extreme temperature and altitude conditions. The laboratory also contains shielded underground storage facilities and a cobalt 60 source of gamma radiation as powerful as some atomic reactors.

Working with radioactive materials is not new to Admiral. For the past seven years the company has been engaged in designing, manufacturing and testing radiation measurement equipment. In this connection Admiral engineers have contributed much to the combined nucleonic-electronic sciences.

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Kudos for Dr. von Kármán

FOR a man accustomed even as Theodore von Kármán is to taking honors in stride, the newest collection of kudos, nevertheless, must have him hard-pressed to keep his step.

Presently, chairman of the Advisory Group for Aeronautical Research and Development, NATO, Dr. von Kármán is world renowned as a scientist and teacher in the field of aeronautical sciences. Occasion for this latest accolade is his 75th birthday.

It started June 18 at Northwestern University's 98th Annual Commencement. Here, fellow ARS member Ali Bulent Cambel, associate professor of mechanical engineering at Northwestern, presented Theodore von Kármán with an honorary Doctor of Science degree.

Two days later, at a birthday dinner at the Biltmore Hotel (Los Angeles), Lt. General Donald Putt, U.S.A.F., bestowed the Presidential Medal of Freedom on Hungarian-born Dr. von Kármán on behalf of President Eisenhower.

Now, a group of Dr. von Kármán's friends plans to honor him by publishing all of his papers not yet in book form sometime this year in a special 75th Anniversary Edition. As presently anticipated, this edition will appear in a set of four volumes, each about 500 pages long.*

* Sets will cost $40 each. There will be a limited number available to individuals only at a prepublication price of $30. Order cards can be obtained from: Publications Committee, Collected Works of Theodore von Kármán, California Institute of Technology, Pasadena, Calif.

On Instrumentation

As part of its 11th Annual Instrument-Automation Conference and Exhibit slated for Sept. 17–21 at New York, Instrument Society of America (ISA) has scheduled five of its sessions, most of them in cooperation with American Rocket Society (ARS) and International Geophysical Year (IGY), on instrumentation topics that should prove of interest to ARS members.

MONDAY, SEPT. 17

10:00 a.m. Statler Hotel

ISA-IGY-ARS Symposium on Instrumentation in IGY

✦ Welcome by Robert T. Sheen, ISA president.

✦ Objective and Plan for the U. S. Participation in the International Geophysical Year, by Joseph Kaplan, chairman, U. S. National Committee International Geophysical Year.

✦ The Role of Instrumentation in Scientific Research Problems, by A. V. Astin and W. A. Wildhack, National Bureau of Standards.

✦ Problems in Instrumentation for the Satellite, by Richard W. Porter, General Electric Co.

2:00 p.m. Coliseum

ISA-IGY-ARS Symposium on Instrumentation in IGY

✦ Scientific Instrumentation in IGY Satellite, by Herbert Friedman, Naval Research Laboratory.

✦ Tracking and Telemetering in the Vanguard Program, by J. T. Mengel, Naval Research Laboratory.

✦ Optical Instrumentation for Satellite Tracking, by J. Allen Hynek and Fred L. Whipple, Smithsonian Astrophysical Observatory, Harvard University.

✦ Computational Program for the IGY Satellite, by Paul Herget, Cincinnati Observatory.

TUESDAY, SEPT. 18

9:30 a.m. Coliseum

ISA-IGY-ARS Symposium on Instrumentation in IGY

✦ Instrumentation in the Meteorology Program of the IGY, by Ervin Volbrecht, U. S. Weather Bureau.

✦ Instrumentation in the Oceanographic Program of the IGY, by Allyn C. Vine, Woods Hole Oceanographic Institution.

✦ Instrumentation in the Rocketry Program of the IGY, by Peter H. Wyckoff, Air Force Cambridge Research Center.

✦ Instrumentation in the Solar Activity Program of the IGY, by John W. Evans, Upper Air Research Observatory.

9:30 a.m. Coliseum

Aeronautical Instrumentation

✦ Missile Flight Test Instrumentation—Panel Discussion. Panel Chairman: Floyd E. Bryan, Douglas Aircraft Co., Inc.

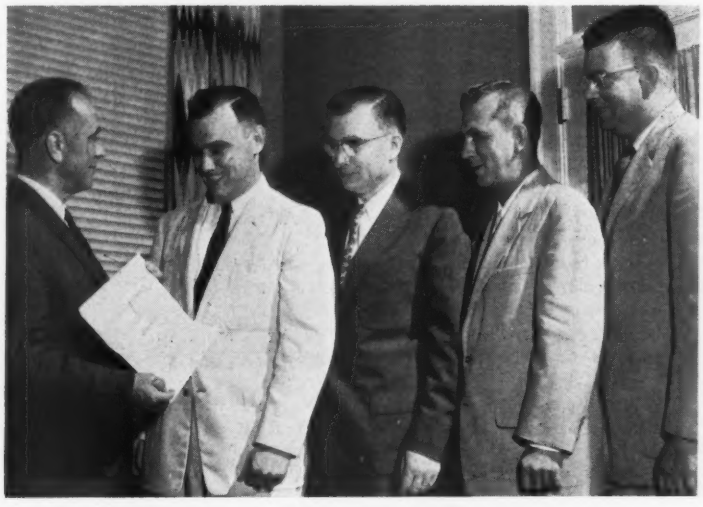
✦ Airborne Reference Junction for Thermocouple Type Temperature Sensor, by Floyd E. Bryan, Douglas Aircraft Co., Inc.

✦ A Light Weight Compact Acceleration Swich for In-Flight Calibration of Accelerometers, by T. A. Perls and R. I. Smith, Lockheed Aircraft Corp.

✦ Problems of Measuring Low Pressures in High Temperatures and High Vibration Environments, by Chester P. Ballard, North American Aviation, Inc.

✦ Brief Discussion of Vanguard Missile Telemetry System, by Henry W. Royce, Glenn L. Martin Co.

✦ Sampling Rates in Flight Testing of Missiles, by Parker Painter, Radiation, Inc.

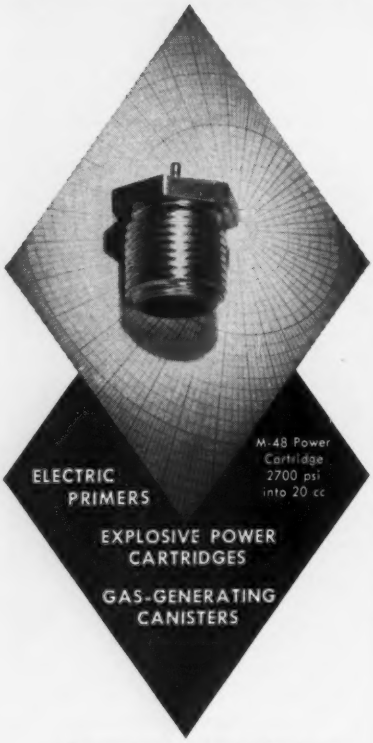


Columbus Section Chartered

At a banquet meeting on June 20, ARS Director S. K. Hoffman (left) presented the Columbus (O.) group with its official section charter. Receiving the charter from Mr. Hoffman are (left to right): M. W. Jack Bell, F. B. Bradley, Edward H. Kelley, and Alexis W. Lemmon, Jr.

Later, Mr. Hoffman, general manager of Rocketdyne, talked about the development of rocket propulsion and future applications of rocket engines, showed slides of Rocketdyne's test facilities.

SQUIB SPECIALISTS



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2:00 p.m. Coliseum

ISA-IGY-ARS Symposium on Instrumentation in IGY

✦ Instrumentation in the Aurora and Airglow Program of the IGY, by L. R. Megill, National Bureau of Standards.

✦ Instrumentation in the Cosmic Rays Program of the IGY, by Robert C. Haymes, New York University.

✦ Instrumentation in the Geomagnetism Program of the IGY, by E. B. Roberts, Coast and Geodetic Survey.

✦ Instrumentation in the Ionospheric Physics Program of the IGY, by Jack Brown, Barker & Williamson.

✦ Instrumentation in the Longitude and Latitude Program of the IGY, by Wm. Markowitz, U. S. Naval Observatory.

Sections

Alabama: The first public showing of the film "Challenge of Outer Space" highlighted the Section's June 28 meeting at Redstone Arsenal. Introduced by Wernher von Braun, the film was made in connection with Dr. von Braun's talks at the Armed Forces College, depicts his ideas for an artificial earth satellite.

Preceding the film, C. H. Dodge of Aerojet-General Corp. spoke to the overflow (more than 500 people) audience about the development and purposes of the Aerobee rocket as an upper atmosphere research vehicle. Mr. Dodge finished his presentation with the film "The Sky Is No Limit" which shows the preparation and launching of an Aerobee.

Northern California: Lending substance to a local tradition of light summer programs, the Section devoted its July 25 meeting to a showing of movies. The triple bill: "Challenge of Space," "Nike for the Defense of America," "2.75-in. FFAR Rocket Story: A Problem in Precision." Approximately 80 members and guests attended.

Worthwhile Words

Putting their pet projects into words paid off for three Alabama high school students last June in an essay contest sponsored by the Alabama Section. Shown above are winners (with checks in hand) and sponsors. In the usual order: Jackie Moon, $15 third prize for "Development and Application of the Principles of Jet Propulsion as Applied to Rockets"; Thomas Gunter, $50 first prize for "Vandergraft Generator"; Conrad Swanson, Section president; C. H. Dodge, guest speaker; Ann King, $25 second prize for "Guided Missile Problems"; Thomas Glynn, essay program chairman.

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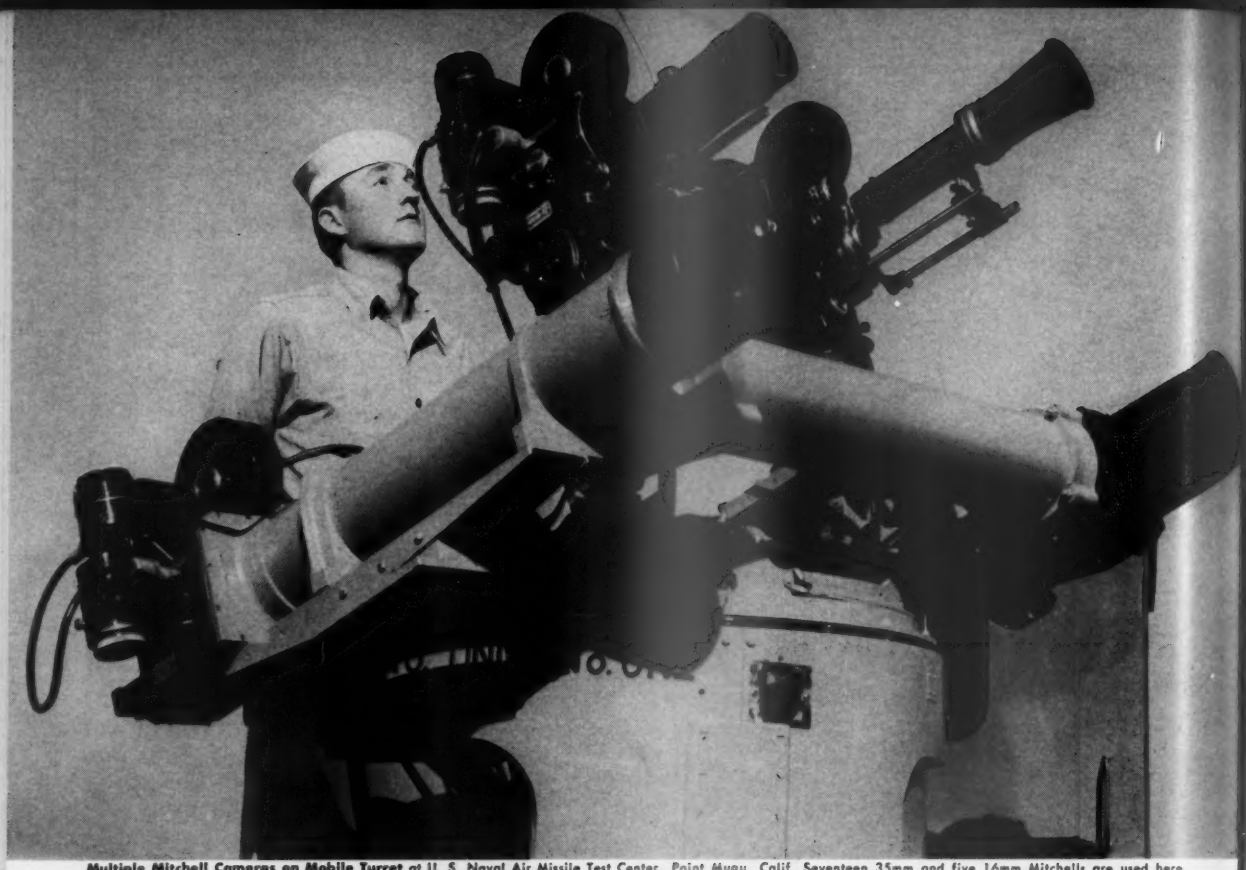


Multiple Mitchell Cameras on Mobile Turret at U. S. Naval Air Missile Test Center, Point Mugu, Calif. Seventeen 35mm and five 16mm Mitchells are used here.

CAMERA BECOMES BASIC RESEARCH TOOL

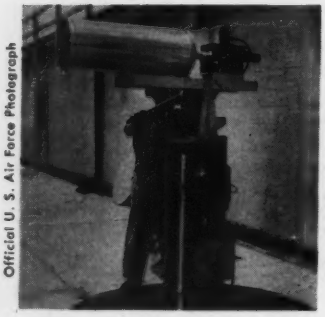
Official U. S. Army Photograph

200 Mitchell Cameras, mostly high-speed models, are in use here at White Sands Proving Ground, New Mexico.

Official U. S. Navy Photograph

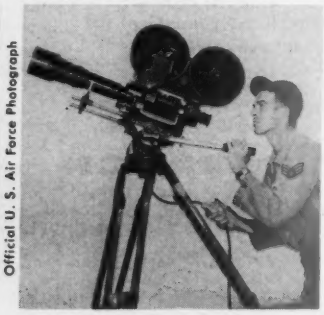
Powered Tracking Mount has Mitchell Cameras; over 50 Mitchells are used at U.S. Naval Ordnance Test Station, Inyokern, Calif.

Mitchell Telephoto Tracking Camera in use at Air Force Missile Test Center, Cape Canaveral, Florida.



Official U. S. Air Force Photograph

One of 12 Mitchell cameras used to track missiles at Holloman Air Development Center, Alamogordo, New Mexico.



Official U. S. Air Force Photograph

Vital Projects Now Heavy Users of Motion Picture Cameras With Flexible Performance Range

Accelerated project work has today put increased demands upon motion picture equipment. Because of the need for a camera which can perform under a broad range of research and development requirements, the Mitchell Camera has today become the standard *basic* motion picture camera used in projects in this country and abroad.

No other single camera can be used so flexibly, under such extreme filming conditions, and for such a broad range of cinematography as can a Mitchell Camera. In one location, alone, 200 Mitchell 35mm and 16mm cameras are now in use at White Sands Proving Ground.

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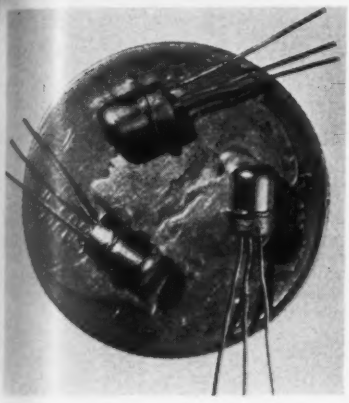
New Equipment and Processes

Equipment

Electrical, Electronic

Induction Heaters. HF electronic heaters, 1–40 kw models, 220 v, 60 cycle. Scientific Electric, 105–119 Monroe, Garfield, N. J.

Subminiature Transistor. M-1 alloy-junction unit withstands 20,000 g. Operates on $^1/_{10,000}$ w. Twenty can be placed on a dime (photo). Amplifier allows 70 db gain. Philco Corp., 4700 Wissahickon, Philadelphia, Pa.



Mechanical

Manifold. Controls gas or fluid flow of rocket propulsion systems. Zero leakage at 4500 psi. Futurecraft Corp., 1717 N. Chico, El Monte, Calif.

Mobile Heavy Duty Crane. Capacity of 5000 lb for jet aircraft, missile use. Weighs 2000 lb. Has rubber tires, needs no electrical power. Cramer-Krasselt Co., 733 N. Van Buren, Milwaukee 2, Wis.

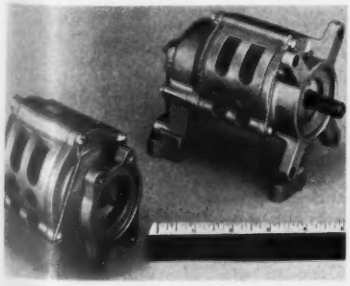
Rocket Fuze. Zinc die cast M405 fuze. Monarch Governor Co., 2800 Tyler Road, Willow Run, Mich.

Hydraulic Actuator. Operates at 800 F, synchronized models. National Water Lift Co., 2200 Palmer, Kalamazoo, Mich.

Tubed Sheet. One flat side aluminum tube used for refrigerating aircraft and missile skins. Reynolds Metals Co., 19 E. 47 St., New York 17, N. Y.

Titanium Wire. Specialty wire. Funk Titanium Corp., Wooster, Ohio. Titanium Fasteners. Standard Pressed Steel Co., Jenkintown, Pa.

Missile Air Motor. Weighs $1^1/_2$ lb, develops $2^3/_4$ hp per 100 psi of inlet pressure. Over-all efficiency about 70% at speeds of 3000–6000 rpm (photo). Bendix Pacific Div., 11600 Sherman Way, North Hollywood, Calif.



High Pressure Regulator. Maximum inlet pressure of 4500 psi for high sensitivity relief and back pressure service. Accessory Products Corp., 616 W. Whittier Blvd., Whittier, Calif.

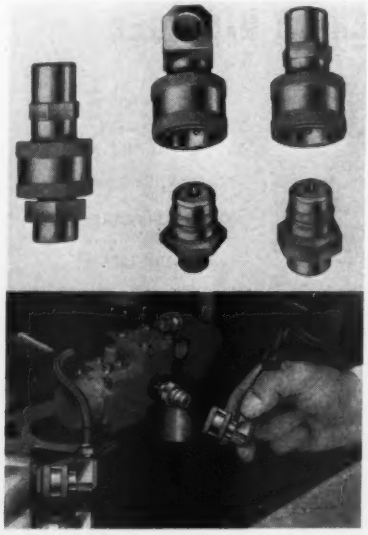
High Damping Mount. W227 mount for low-frequency vibration. Stainless steel construction for static load deflection of $2^1/_2$ in. Frequency of 2 cps. Vibration isolation of 85% at 6 cps and over. Robinson Aviation Inc., Teterboro, N. J.

Barometric Pressure Switch. Model GB-300 of min'ature design can open or close circuit at any altitude from 1000 to 50,000 ft. Gorn Electric Co., Stamford, Conn.

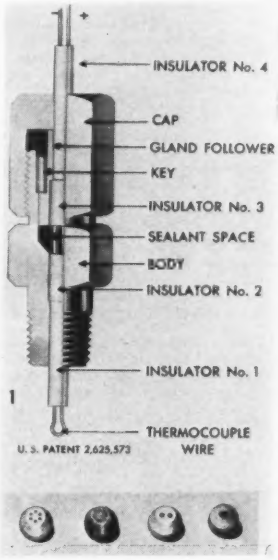
D-C Solenoid Shut-Off. Model 21A for missile use. Ranges to 3000 psi, −65 to 275 F, drain 1.5 amp at 30 v dc. Stainless steel, Teflon construction (photo). National Aircraft Corp., 3411 Tulare, Burbank, Calif.

Micro Drill. For drilling holes down to 0.001-in. diam. Magnetic driven. Micrometer depth control permits stop to within 0.0002 in. Dunmore Co., Racine, Wis.

Quick Disconnect Couplings. For pressures to 1500 psi, $^1/_8$ in. ANPT (photo). Eastern Industries, 100 Skiff St., Hamden 14, Conn.



Lava Sealant. Magnesium silicate seals to 20,000 psi and temp of −300 to 1850 F. Conax Corp., 7811 Sheridan Drive, Buffalo 21, N. Y. (photo).



Pump. Centrifugal type can be used for abrasive materials such as fine solids. Allen-Sherman-Hoff Co., 259 Lancaster, Wynnewood, Pa.

Heat Transfer Units. Serpentine construction available in widths from 18 to 22 in. and lengths from 23 to 119 in. Tranter Mfg., Lansing 4, Mich.

Test

Missile Camera. Traid 100 stands 1000 g. Film speeds of 64, 128, 200 fps, 100-ft capacity. Cylindrical $10^1/_{32}$ in. long × $4^5/_{16}$ in. diam. Weighs 5 lb. Traid Corp., 4515 Sepulveda, Sherman Oaks, Calif.

Hand Pyrometer. Model 321 has 19-in.-long probe of chrome-alumel (to 2300 F) or iron-constantin (to 1600 F). Pacific Transducer Corp., 11836 W. Pico, Los Angeles 64, Calif.

Nondestructive Tester. For bonded materials in missiles uses ultrasonics. Allen B. DuMont Laboratories, 750 Bloomfield Ave., Clifton, N. J.

Flow Meter. No pressure drop, no exposed elements. For liquids or gases. Industrial Development Laboratories, 17 Pollack, Jersey City 5, N. J.

Missile Tester. Unit electronically simulates firing conditions and is used on FALCON (photo). Electronic Engineering Co., 180 S. Alvarado, Los Angeles 57, Calif.

ENGINEERS

ARMA announces

INERTIAL NAVIGATION

development program for an advanced Air Force missile

Inertial Navigation offers the most advanced concept in guidance, requiring no terrestrial source of energy or information, no earth-bound direction once the ultimate destination is selected. It offers the most promising solution of the guidance problem for the long-range missile.

While the principles are simple, the realization involves advanced creative engineering. ARMA's many successes in the creation of precision instruments and systems for navigation and fire control, especially precision gyroscopic reference systems for all applications, fit it uniquely for a major role in this advanced area.

The height of imaginative resourcefulness and engineering skill are required to create the degree of precision—hitherto unattained—in the components essential to the guidance of advanced missile systems—the gyros, accelerometers, and computer elements. Miniaturization must be coupled with extraordinary ability to provide utmost accuracy under conditions of extreme velocities, temperatures, and accelerations.

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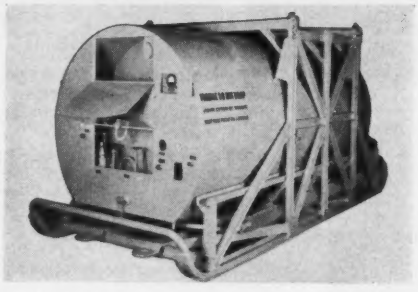

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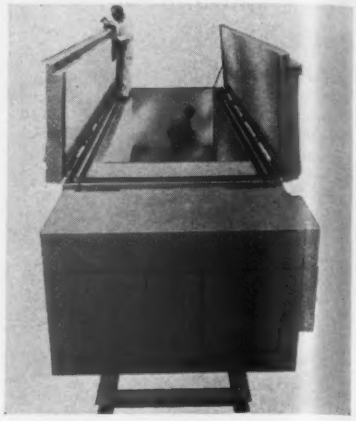
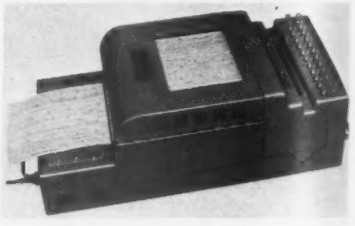
Rocket Motor Box. Complete motor can be lowered into conditioning box (20 ft × 6 ft × 6 ft) and subjected to −100 to 170 F (photo). Moore & Hanks Co., 9702 Rush St., El Monte, Calif.



Electrograph. Model 420, 24 channel produces 8-in.-wide oscillograms that may be read instantly after recording. Lines can cross one another. 100 cps without amplification. Century Electronics & Instruments, Inc., 1333 North Utica, Tulsa, Okla. (photo).



Motion Analysis Camera. 16-mm camera takes 5000 pictures per sec. Also airborne model and a missile hit-miss model. Also used in rocket sled tests. Fairchild Camera and Instrument Corp., Robbins Lane, Syosset, N. Y. (photo).

X-Y Plotter. Model 200A responds to analog or digital inputs while Model 200B accepts d-c voltages as inputs. Librascope, Inc., Glendale 1, Calif.

Gyro Calibrator. Model C181 rate of turntable tests rate gyros for low g forces. Genisco, Inc., 2233 Federal Ave., Los Angeles 64, Calif.

Soundscope. MSA combines sound level meter, octave band, and narrow band analyzer. Mine Safety Appliances Co., 201 N. Braddock, Pittsburgh 8, Pa.

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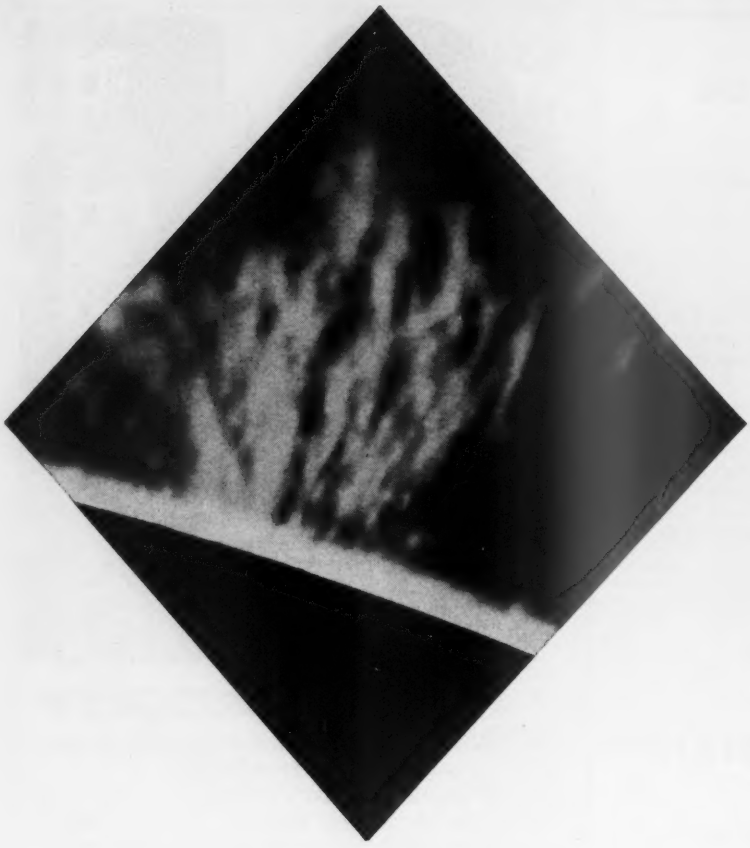

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If you are interested in this immense field of research and development, contact J. M. Hollyday, Dept. JP-09, The Martin Company, Baltimore, Maryland.

MARTIN

Schlieren Camera. For operation inside supersonic wind tunnels. Sherman Fairchild, 30 Rockefeller Plaza, New York, N. Y.

Recording Oscillograph. Model 158-5490 has 8 channels, is housed in mobile cabinet. Frequency response to 20 cps. Rectangular coordinates, chart speeds of 0.25–100 mm/sec (photo). Sanborn Co., 195 Massachusetts Ave., Cambridge 39, Mass.

Iono-Chamber. Model 550 simulates pressures up to 150,000 ft (100 microns of Hg) within 60 sec and from 150,000 ft to 350,000 ft (0.1 micron) in an additional 60 sec. Working space is 18 in. ID × 30 in. deep. Hudson Bay Div., Labline, Inc., 3070 W. Grand, Chicago 22, Ill. (photo).

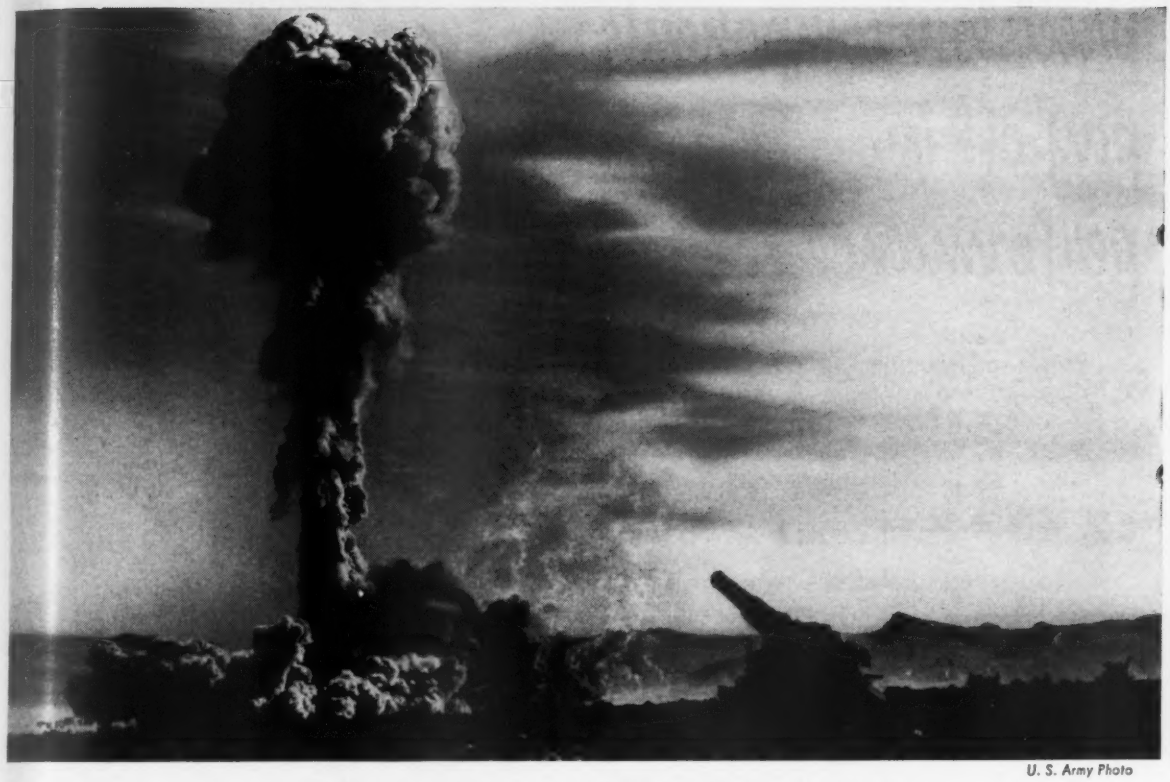
Chemicals

Lockfoam. Foamed-in-place cellular plastic. Nopco Chemical Co., Harrison, N. J.

One Package Epoxy. Adhesive No. 509 is nontoxic, nonflammable, for elevated cure only. Amchem Corp., 283 Tuxedo, Highland Park 3, Mich.

Hydroxylamine Nitrate. Powerful reductant available in 18.5% aqueous solution. Southwestern Analytical Chemicals, 1107 W. Gibson St., Austin 4, Tex.

Kel-F Grease. Fluocarbon lubricant No. 90 resists strong acids, oxygen, ozone,



U. S. Army Photo

Firing of 280 mm Atomic Shell at Las Vegas Proving Ground in May, 1953. This shell was designed jointly by Picatinny Arsenal and Los Alamos engineers and scientists.

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Picatinny Arsenal at Dover, N. J., is composed of a group of Ammunition Development Laboratories responsible for Army ammunition technical development. Its responsibilities include research and development of ammunition for artillery, mortars, and recoilless rifles, mines, grenades, warheads for bombs and guided missiles, and rocket propellants.

One of Picatinny's principal laboratories is the Atomic Applications Laboratory, which is responsible for Army research and development of atomic munitions. This Atomic Applications group operates as the nerve center for all activities in atomic development for the Department of the Army.

To execute its mission responsibility, the Atomic Applications Laboratory draws not only on its "in-house" capabilities, but on the facilities of other Army arsenals, proving grounds, and on industry. Its "in-house" capabilities include an engineering technical organization that uses the full facilities and capabilities of the arsenal.

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The scientific personnel in organizations such as the Atomic Applications Laboratory will determine America's ability to meet potential aggressors with the most effective Atomic Weapons possible.

This is one of a series of ads on the technical activities of the Department of Defense.

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Kel-F Elastomers. Resins contain 50% fluorine, are resistant to such rocket materials as RFNA, 90% peroxide, fuming sulfuric, etc. M. W. Kellogg Co., Box 469, Jersey City 3, Mo.

Epoxidized Olefins. Available as octylene oxide, dodecene oxide, and C_{16}-C_{18} olefin oxide. Becco Chemical Division, Station B, Buffalo 7, N. Y.

Rubber Seal. Acid resistant to prevent leakage at wrists and ankles of rocket handling suits. Dayton Rubber Co., Dayton, Ohio.

Hermetic Sealing. Thiokol liquid polymers for electrical wiring systems, cycles from −65 to 300 F (photo). Thiokol Chemical Corp., 780 N. Clinton, Trenton 7, N. J.

Nitrosoguanidine. Cool, flashless primary explosive and propellant. Shipped only with 10–20% water added. Redel, Inc., 401 E. Julianna St., Anaheim, Calif.

Materials

Basaltwool. Heat and sound insulator withstands 1450 F for use in test cells, etc. Thermo-Sound Products, 714 W. Olympic Blvd., Los Angeles 15, Calif.

Polyethylene Tanks. Self-supporting for handling corrosive chemicals. American Agile Corp., Box 168, Bedford, Ohio.

Silicone Rubber. For molded and extruded parts. Garlock Packing Co., Palmyra, N. Y.

Processes

Ducting. High temperature ducts for jet aircraft (weighing about ½ conventional ducting of equal strength) are now being fabricated of laminated fiberglas. Narmco Manufacturing Co., 5159 Baltimore Drive, La Mesa, Calif.

Product Literature

Available free, unless otherwise stated to those who request them on company letterhead.

Expansion Joints. Catalog no. 53 gives construction details with application data for piping systems. Cook Electric Co., 2700 N. Southport Ave., Chicago 14, Ill.

Miniaturization. 20-page brochure describes advantages of weight and volume reductions. Standard Pressed Steel Co., Box 735, Jenkintown, Pa.

Thermal Properties of Gases. Tables give thermodynamic, transport properties of air, argon, carbon dioxide, hydrogen,

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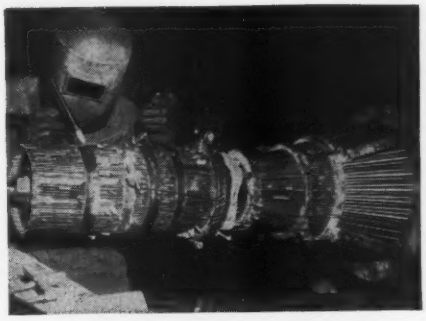

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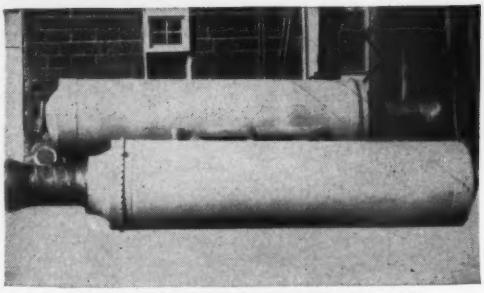

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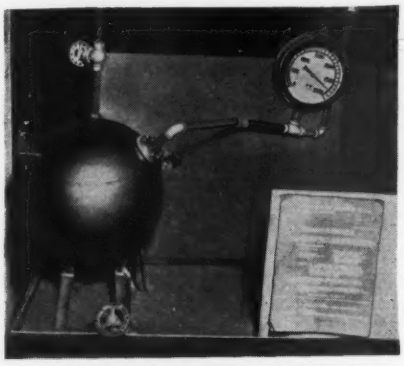

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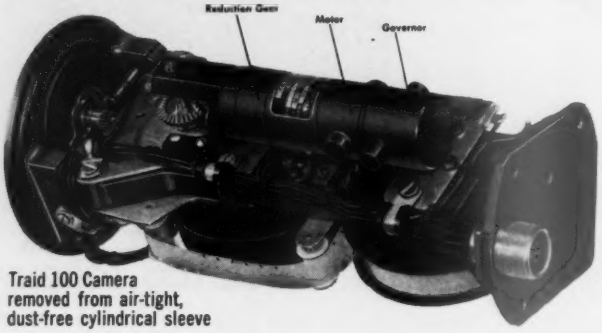
MISSILE CAMERA

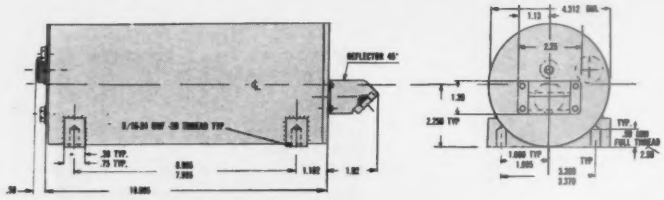
A Report on the Ejectable, Floatable, Shock Sustaining Traid 100 Camera

Safe recovery of film after ejection from a missile at an estimated 1,000 g's shock acceleration has been assured by repeated tests of the Traid 100 Camera. Tests prove that the camera can withstand a free fall of 300 feet without exhibiting light leaks or sustaining film damage. Recent centrifugal tests at Lockheed's Missile Division, Van Nuys, Calif., proved that the Traid 100 Camera functioned perfectly at 128 f.p.s. under 25 g's applied in both directions of the three major axes.

The ejectable feature of the Traid 100 is coupled with parachute suspension. Its unusual ruggedness, its ability to float, the ease of mounting and its reliability of operation make this camera especially useful in both military and civilian testing.



Traid 100 Camera removed from air-tight, dust-free cylindrical sleeve



TECHNICAL DATA AND OPERATING CHARACTERISTICS

POWER: Consumes 3 amps at 28V-DC. Starting surge 6 amps . . . **MOTOR:** 28V-DC, permanent magnet, governor controlled . . . **SHUTTER:** Aluminum rotary disc, 204° standard . . . **EXPOSURE:** 1/28 sec. at 16 fps (with 204° shutter), 1/350 sec at 200 fps. . . . **SPEEDS:** Standard camera 64 fps only. Also available 128 fps only, 200 fps only and gear train assemblies of 16, 24 and 32 fps. for use with 64 fps camera. . . **LENS MOUNT:** Single lens—"C" thread . . . **STRUCTURE:** Camera assembly mounted on single heavy aluminum casting surrounded by tubular aluminum or steel case. All joints and openings are AIR and WATER TIGHT . . . **FILM:** 16mm, 100 ft. daylight loading spool. . . . **WEIGHT:** Five pounds. . . . **DIMENSIONS:** Diameter 4-5/16" x 10-3/32" **ACCELERATIONS:** Operation at 25 g's in all direction guaranteed. Film perfect after 1000 g's shock.

OPTIONAL FEATURES

CAMERA CASE: Choice of steel or non floating aluminum . . . **CHANGE GEARS:** Choice of 16, 24, 32, 64 fps . . . **FLOATATION:** Light Aluminum FLOATING Case and casting . . . **VIEWFINDER:** Positive, parallax correcting . . . **LIMITING SWITCH:** Automatic power cut off at end of run . . . **CORRELATION SWITCH:** Provides impulse of each frame to counter . . . **TIMING SYSTEM:** Single or two light system.

NEW ACCESSORIES

LENS MOUNT: Interchangeable gun camera mount assembly . . . **CAMERA MOUNT:** Complete spare aluminum or steel camera case with 4 hole mounting brackets . . . **GEAR CHANGE BOXES:** Extra interchangeable gear assemblies for speeds of 16, 24, 32, 64, fps . . . **RADIO INTERFERENCE FILTER:** Exterior plug-in attachment . . . **BORESIGHT:** Variable 15 to 34X ocular . . . **PARACHUTE MOUNTING:** Two stainless steel studs for parachute . . . **SEALED QUARTZ LENS COVER:** High-pressure sealed quartz for 15mm f/2.5 lens.

A full line of high speed and data recording cameras is manufactured by the Traid Corporation. Complete engineering services in the field of photographic research are available to science, industry and for military requirements.

The completely new Traid Catalog containing fully detailed and illustrated technical data, operational characteristics, with prices on equipment and accessories, is available upon request. Address D11, Traid Corporation, 4515 Sepulveda, Sherman Oaks, Calif.

nitrogen, oxygen, and steam. Catalog no. C 13.4:564, 1955. Superintendent of Documents, Government Printing Office, Washington 25, D. C. $3.75.

Swaged MgO. Instructions for using swaged magnesia wire. Aero Research Instrument Co., Chicago, Ill.

Record Heads and Magnetic Drums. 4-page bulletin details data handling systems, computer memory systems. Librascope, Inc., 808 Western, Glendale, Calif.

Photosensitive Devices and Cathode Ray Tubes. 24-page catalog describes line of pototubes, TV camera tubes, and CRT's. RCA Tube Div., Commercial Engineering, Harrison, N. J. $0.20.

Ethane-Nitrogen Properties. Physical and chemical properties of ethane-nitrogen mixtures are given in Research Bulletin 26. Institute of Gas Technology, Technology Center, Chicago 16, Ill. $5.

Material Test Machines. Bulletin RG-14-55 describes creep testing machine and portable hardness tester. Riehle Testing Machines Div., American Machine & Metals, Inc., East Moline, Ill.

Solar Cells. New line of selenium cells are listed in Bulletin SR-115. International Rectifier Corp., 1521 E. Grand, El Segundo, Calif.

Aluminum Bronze. Tuf-Stuff alloys are light, tough, corrosion resistant, and easily worked. Mueller Brass Co., Port Huron, Mich.

Nickel-Steel Alloys. Bulletin A-68 gives properties, sizes, etc. International Nickel Co., 67 Wall St., New York 5, N. Y.

Lead Sulfide Photoconductor. New booklet describes Kodak Ektron Detector. Gives characteristics, applications. East-

engineer

FOR CRUCIAL AREA OF TEST-RESULT EVALUATION IN ADVANCED AIRCRAFT PROPULSION

Now the Aircraft Gas Turbine Division of General Electric offers the young engineer a first-hand opportunity to be the liaison between test and factory, plan test programs, supervise engine assembly, specify instrumentation, describing each project he undertakes in an official report.

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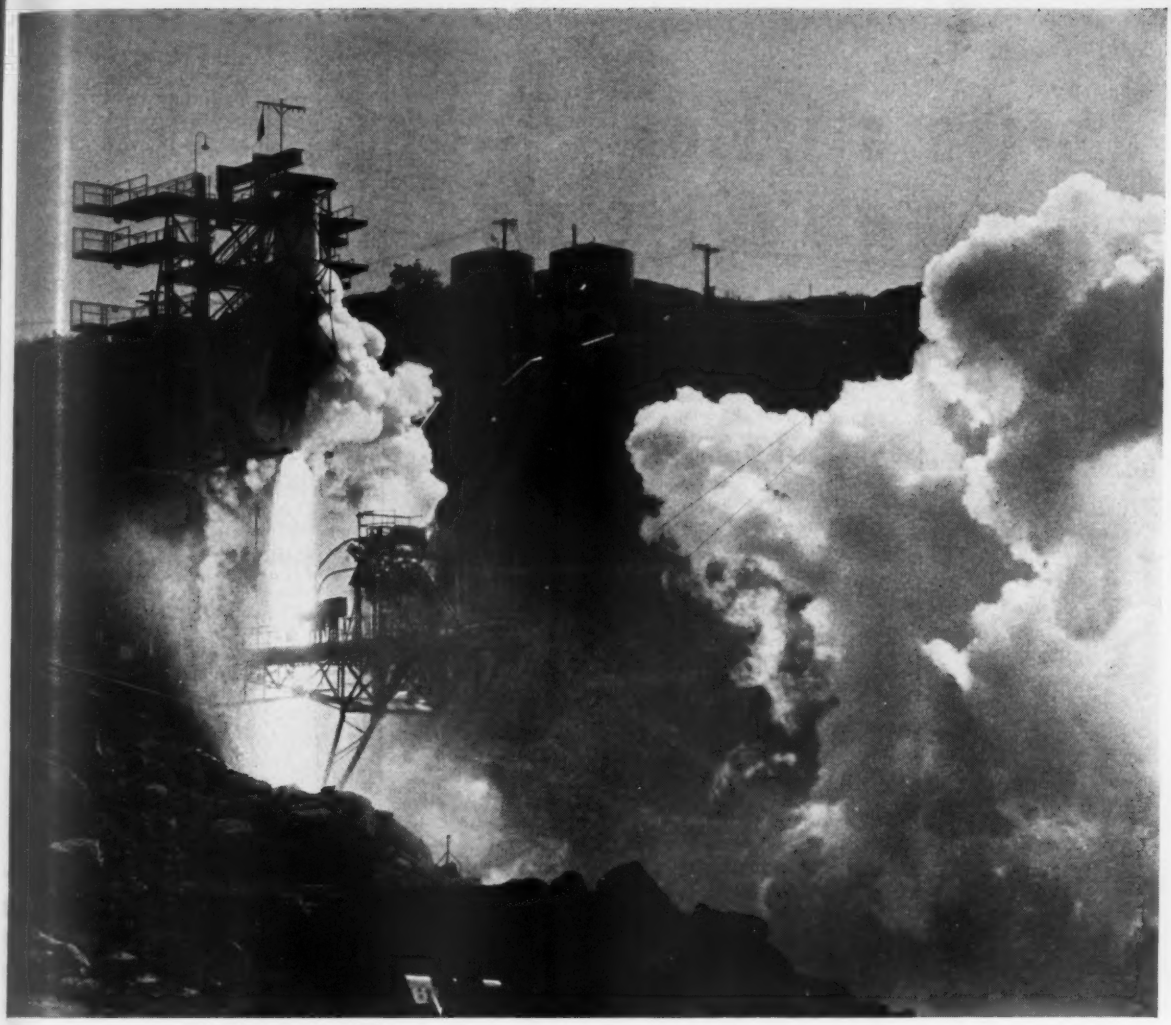

Actual test firing of a modern ROCKETDYNE rocket engine at the Field Test Laboratory in the Santa Susana Mountains.

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Today's rocket engines are the most powerful in the world... and the power they develop is helping to make our nation's long-range guided missile program an operational reality.

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For the past 10 years ROCKETDYNE has been working closely with the Department of Defense, producing its rocket engines as required, and delivering them on time. New and more powerful rocket engine designs for tomorrow's more effective missiles are in constant development.

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missile engineers

CONTROL GUIDANCE SERVO COMPUTERS RECORDING OPTICAL RELIABILITY ELECTRO-MECHANICAL TELEMETERING

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Flight Test Engineering Section, which plans the missile test programs and establishes test data requirements in support of the programs. The data requirements are predicated on the test information required by the Engineering analytical and design groups to develop and demonstrate the final missile design, and are the basis from which the instrumentation requirements are formulated.

The analysis work performed consists of aerodynamic, missile systems, dynamics, flight control, propulsion and guidance evaluation. The Flight Test Engineering Section is also responsible for the field test program of the ground support equipment required for the missile.

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There are now a number of openings available for engineers in each of these groups at all experience levels.

If you qualify for any of these challenging opportunities, we invite you to contact Engineering Industrial Relations, Plant 2, Gate 3B, Broadway & Prairie, Northrop Aircraft, Inc., Hawthorne, California; or write Manager of Engineering Industrial Relations, Northrop Aircraft, Inc., 1021 East Broadway, Hawthorne, Calif.

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PIONEERS IN ALL WEATHER AND PILOTLESS FLIGHT

Producers of Scorpion F-89 Long-Range Interceptors and Snark SM-62 Intercontinental Missiles.

5-A-65

man Kodak Co., 343 State Street, Rochester 4, N. Y.

Template Catalog. Lists over 100 templates for drafting and engineering use. A. Lawrence Karp, 16 Putnam Park, Greenwich, Conn.

Supersonic Heat Transfer. Bulletin 55SD3 describes skin temperatures and pressures on V-2 nose cone. General Electric Co., 2900 Campbell Ave., Schenectady 5, N. Y.

Swaged Magnesia Insulation. Bulletin 4 details insulation, connectors for making thermocouple junctions for wires at 2000 F and higher. Aero Research Instrument Co., 1040 W. Grand Ave., Chicago 22, Ill.

Pressure Switches. Catalog CGC describes line of new pressure switches. Century Electronics & Instruments, Inc., Tulsa, Okla.

Noise Control. Air Force supplement is called "Handbook of Acoustic Noise Control, Vol. I, Physical Acoustics," PB-1112-00S. Available from Office of Technical Service, U. S. Dept. of Commerce, Washington 25, D. C. $8.

Magnetic Ceramics. "Study of Magnetic Ceramics," CRB-111625. Available from Office of Technical Service, U. S. Dept. of Commerce, Washington 25, D. C. $1.75.

Propulsion Research. Eight-page brochure describes engineering services and products. Propulsion Research Corp., 1860 Franklin, Santa Monica, Calif.

Molecular Aluminum Bonding. Describes Alumibond process for bonding to iron and steel alloys. Arthur Tickle Engineering Works, 21 Delavan St., Brooklyn 31, N. Y.

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Experienced Aeronautical or Mechanical engineer wanted to supervise basic and applied research on the internal and external aerodynamic characteristics of jet engine exhaust systems. Extensive research facilities, including an 8-ft. high-speed subsonic tunnel and new 17-in. transonic and supersonic wind tunnels, are available for experimental work.

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United Aircraft Corporation
East Hartford 8, Conn.

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explosive-actuated devices

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Severs cable up to 1⅛ inches diameter, initiated over a simple electrical circuit requiring a minimum of 5000 ergs. One of several types used in missiles and aircraft for separating structural and electrical cables, oil lines, etc.

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New Patents

George F. McLaughlin, *Contributor*

Continuity tester for rocket motors (2,744,236). O. D. Scarborough, Hastings, Neb., assignor to the U. S. Navy.

Electrical tester for squib detonators. Continuous belt with cradle supports conveys the motors in and out of a chamber where personnel may test detonators at safe distances.

Method of generating jet power through sulfide reaction (2,744,380). Edward B. McMillan, Wakefield, and Dudley F. Straubel, Malden, Mass.

Process of creating and projecting finished jet material by supplying to a combustion zone a burst of reducing agent reactants in molten form under high pressure.

Removable inflatable protective closure for jet engine (2,744,382). Benjamin Sokol, Valley Stream and August Di Florio, Rosedale, N. Y., assignors to Republic Aviation Corp.

Hollow longitudinally circular tube having a flap on one end adapted to overlap the other end of the tube, and means for inflating it to expand it both radially and laterally against the housing wall.

Gas turbine plant (2,744,383). Marcel Henri L. Sédille, Paris, France, assignor to Société Rateau (Société Anonyme).

Auxiliary turbine adapted to drive air and combustible gas compressors at a speed equal to the value of the operating point of the compressors at maximum efficiency. Also, means for delivering an extra amount of thermal energy in the form of liquid fuel to the combustion chamber, regulated by a valve.

Cosmic ray altimeter (2,744,697). James A. Van Allen, Iowa City, Iowa, assignor to the U. S. Navy.

Means in an aerial missile and responsive to cosmic radiation when the missile is in flight in the upper atmosphere, and means responsive to a voltage output of an electrical circuit for controlling the altitude of the missile.

High speed aircraft wing and tail surfaces having variable sweepback (2,744,698). Leslie E. Baynes, Hounslow, England, assignor to Baynes Aircraft Interiors Ltd.

Control means operable while the jet aircraft is in flight for varying simultaneously the sweepback of the wings and tail surfaces between an extended position for low speed flight and a sweptback position for high speed flight.

Contact and stop mechanism for (rocket) launchers (2,742,820). Robinson Brown, Hugh E. Metcalf, and John F. Brooks, San Antonio, Tex., assignors to the U. S. Army.

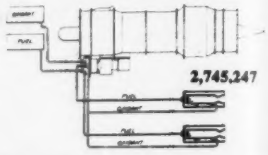
To release a rocket for launching, a plunger is mounted on a tube for outward movement in response to forward motion of the rocket from a predetermined firing position. A pin on the plunger engages and stops the rocket in firing position short of the plunger face.

Propellant impelled turbine (2,743,576). Sydney Robert Crockett, China Lake, Calif., assignor to the U. S. Navy.

Pressure chamber connected to a container for propellant receives combustion gases when the propellant is ignited, driving a turbine rotor. A governor responsive to the angular velocity of the rotor controls the extent of opening of control ports, maintaining the rotor velocity constant.

Rocket engine control (2,743,577). Emil A. Malick, Bartlesville, Okla., assignor to Phillips Petroleum Co.

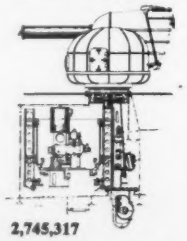
Engine adapted to be launched from an aircraft. Release mechanism jettisons the engine at a preselected time interval following initial passage of fuel and oxidant to the combustion chamber.



2,745,247

Rocket assisted composite engine arrangement (2,745,247). Dietrich E. Singelmann and James R. Hall, Buffalo, N. Y., assignors to Bell Aircraft Corp.

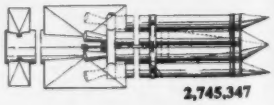
Turbojet engine with a pump-fed rocket-type auxiliary thrust engine. The pump, mounted on a power take-off pad, is driven by the accessory gear system.



2,745,317

Missile Launcher (2,745,317). Arthur J. Stanton, Robert E. Carlberg, Frank W. Sieve, William Danziger, and Rocco De Masi, Arlington, Va.

Structure mounted for rotation and a guide for directing the initial flight of missiles in rapid succession. The guide is supported for oscillating movement from an inclined firing position to a vertical loading position.



2,745,347

Self-projected missiles (2,745,347). Alexander Lightbody and James M. Johnson, Baginton, England, assignors to W. G. Armstrong Whitworth Aircraft, Ltd.

Discardable wrapped round boost motors secured to the missile at two axially-spaced places. When the thrust of the motors is sufficiently great, releasable catches connecting the frame member (carrying the motors) are held in contracting position.

Convertible pulsejet and ramjet engine (2,745,248). James S. Winter, George W. Kallal, and James J. Mazzoni, Richmond Heights, Mo., assignors to McDonnell Aircraft Corp.

While the engine is operating as a ramjet, a sleeve in the air inlet tube is moved to prevent airflow through a tubular valve

EDITOR'S NOTE: The patents listed above were selected from recent issues of the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained at a cost of 25 cents each, from the Commissioner of Patents, Washington 25, D. C.

expand your oscillograph capacity as your needs demand...

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Magnet assemblies accommodate from 1 to 12 active galvanometers plus 2 static reference traces each
Series 700C oscillographs provide 1 to 60 channels
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Panel for 115 volt 50-to-400 cycle AC power input

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- Use the same instrument on DC or AC . . . just specify the proper power supply panel.
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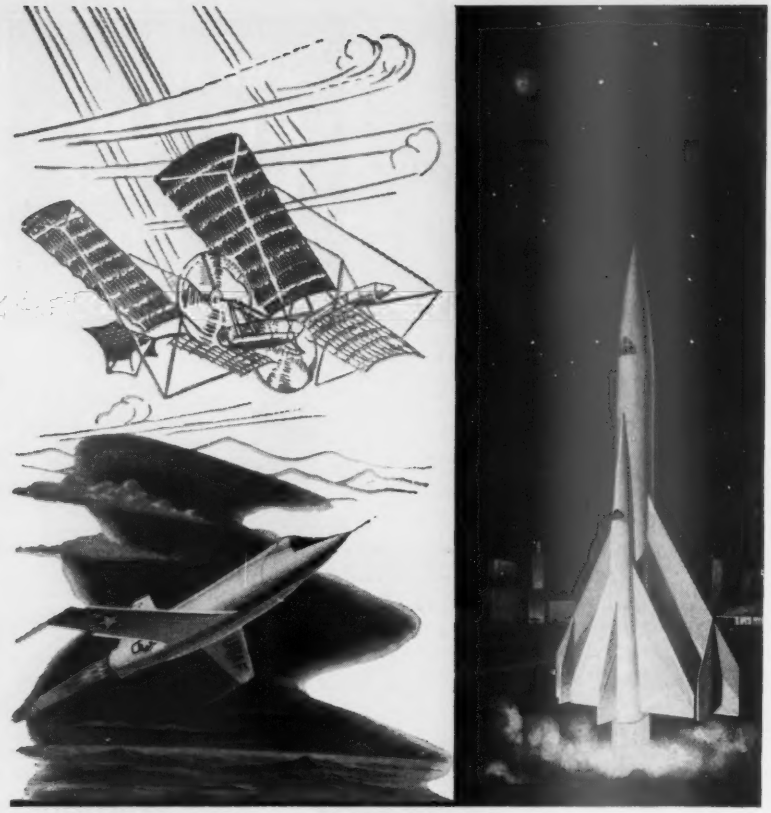

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In his attempts to fly, man tried many methods of propulsion... flapping wings... vacuum globes for lift... steam engines... and oar-propelled gas balloons. But — it took the genius of the Wright Brothers to combine earlier experiments with a light-weight gasoline engine to finally achieve flight. A giant step in science separates this early 12 hp engine from today's powerful jets, capable of over 60,000 hp in thrust, or that most potent of all modern engines, the rocket engine.

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BELL Aircraft CORPORATION

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connected to one end of the casing. While the engine is operating as a pulsejet, air is directed into the valve.

Reheater and fuel vaporizer for jet propulsion engines (2,745,249). Daniel S. Sanborn, Palos Verdes Estates, Calif., assignor to The Ryan Aeronautical Co.

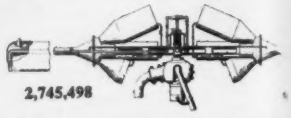
Temperature sampling bulb in a diverging diffuser section controls the speed of the motor. Fuel pump increases delivery when the temperature drops and decreases delivery when the temperature rises.

Reverse vortex combustion chamber (2,745,250). Robert H. Johnson and Raymond H. Shackelford, Schenectady, N. Y., assignors to General Electric Co.

Air inlets composed of angularly directed nozzle openings for vortical admission of combustion and cooling air to the combustion chamber.

Apparatus for atomization of a liquid fuel (2,745,251). Robert M. Schirmer, Bartlesville, Okla., assignor to Phillips Petroleum Co.

Measuring devices associated with a fuel atomizer vary the air supply in response to linear air velocity and density.



2,745,498

Rocket-driven helicopter rotor (2,745,498). Bruno Nagler, Boston, Mass., assignor to Nagler Helicopter Co.

Rocket motors carried on manifolds in horizontally disposed blades. The motors direct fluid under pressure for discharge to the atmosphere by way of jets at the blade tips.

Jet propulsion and boundary layer control system for aircraft (2,745,611). Marcel Henri L. Sedille, Paris, France, assignor to Société Râteau (Société Anonyme) and Rene Anxionnaz.

Wing surfaces with spanwise suction slots for sucking up the boundary layer of atmospheric air. Slots are staged at different levels between the leading edges and trailing edges of wing surfaces. One air compressor is disposed in each channel in the slot to discharge air into a chamber connected with the air intake side.

Pressure responsive indicating, sensing, and controlling devices (2,746,242). Wendell E. Reed, Chula Vista, Calif., assignor to Solar Aircraft Co.

Turbojet engine with a differential pressure responsive device which operates to control means for varying the turbine discharge pressure.

Variable nozzle, and sealing means therefore, for jet engine (2,746,243). Paul A. Pitt and Morris E. Nelson, San Diego, Calif., assignors to Solar Aircraft Co.

Pair of movable gates on opposite sides of the tailpipe shaped to form a sealed extension with a reduced discharge orifice when closed. The gates are retracted, clear of the exhaust, to permit passage of cooling air through the discharge pipe.

Reaction power plant variable discharge area nozzle control system (2,746,244). John H. Baker, Washington, D. C., assignor to General Electric Co.

Reciprocable actuating member for opening and closing the discharge nozzle. A differential device driving the actuating member is connected to two input connections; a nozzle adjusting activator is connected to one, and a quick release nozzle closing device is connected to the other.

Freeze prevention in jet aircraft purge gas generators (2,746,245). Henry A. Geisler and Roger J. Queisser, Indianapolis, Ind., assignors to Stewart-Warner Corp.

● Manufacturing ●● Manufacturing and product development ●●● Manufacturing, product development and research □●● Pilot manufacturing, product development and research

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	GPE CAPACITIES
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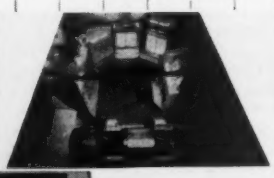
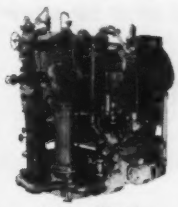
●●●			●●●	●●●	●●●	●●●				●●●		●●●	SYSTEMS ENGINEERING

Librascope Desk-Size Computer



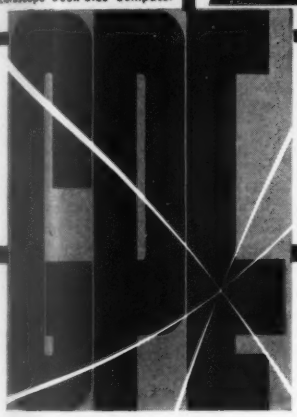
Link Aviation F-89D Jet Simulator

GPL Industrial-Institutional TV System



Griscom-Russell Shipboard Distilling Plant

Askania Electro-Jet Power Package



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Means for feeding fuel to a combustion chamber. Apertures admit compressed air, and nozzles deliver toward the blades the gases from the chamber to a stationary U-shaped annular member.

Fuel control and regulating system for turbojet and turboprop engines (2,746,247). James W. Bevins, Ramsey, N. J., assignor to Bendix Aviation Corp.

Automatic control responsive to engine speed for operating fuel flow valve. Mechanical means permit disconnecting or resetting valve to obtain desired engine speed.

Compressor deicing and thrust balancing arrangement (2,746,671). Phillip P. Newcomb, Manchester, Conn., assignor to United Aircraft Corp.

Tube inside hollow inlet guide vanes and having openings for directing fluid against a selected portion of the inner surface of the surrounding vane.

Compressor blading (2,746,672). Walter Doll, Jr., Phillip Martsolf, Jr., and Carl R. Soderberg, Jr., Lincoln, Mass., assignors to United Aircraft Corp.

Blade cambered so that gasses are directed through a predetermined pattern of turning. One end is overcambered beyond that normally required, causing the trailing edge to be a warped line.

Jet propulsion plant with interconnected afterburner and jet nozzle area control (2,747,363). Henry Cohen and John H. H. Darth, Sutton, England, assignors to Power Jets (Research and Development).

Obturating means to increase the jet nozzle area when the supply of fuel to the burner is turned on.

Two-way rotary fluid valve (2,747,364). Sidney H. A. Magin, London, England, assignor to D. Napier & Son, Ltd.

Cylindrical chamber in which passages maintain a fluid path of substantial cross-sectional area at all positions of the rotary valve member.

Supply of hot air from a gas turbine engine for anti-icing or other purposes (2,747,365). H. S. Rainbow, Coventry, England, assignor to Armstrong Siddeley Motors, Inc.

Intermediate section inner and outer casings interconnected by airfoil section spokes. Channel-section members at the outer ends of spokes form a closed section casing into which hot air is supplied through a valve.

Starting system for ramjets (2,747,366). Robert T. Barnes and George D. Lewis, Manchester, Conn., assignors to United Aircraft Corp.

Primary regulator for controlling fuel flow responsive to a parameter of power plant operation, and an independent secondary control of the regulator during starting.

Gas turbine power plant supporting structure (2,747,367). Bennett S. Savin, Wethersfield, Conn., assignor to United Aircraft Corp.

Bearings carried by a frame for separately supporting each compressor rotor at opposite ends. Mountings for bearings extend between frame and bearings.

Engine temperature responsive means to control fuel supply by-pass and spill lines (2,747,369). O. N. Lawrence, Dorridge, England, assignor to Joseph Lucas (Industries) Ltd.

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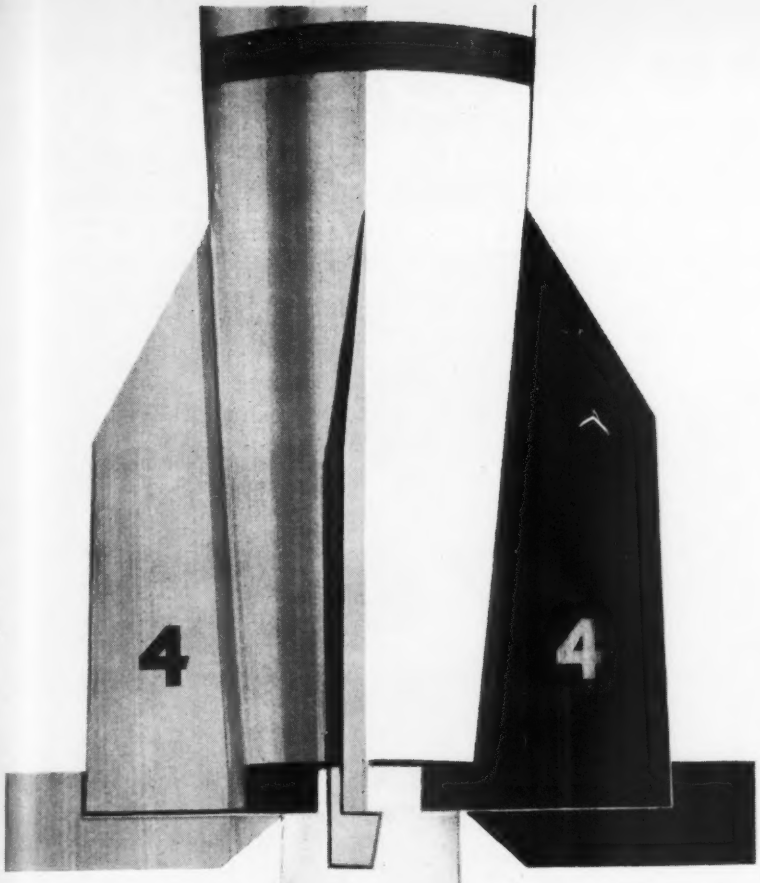

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Gas Turbines for Aircraft, by Ivan H. Driggs and Otis E. Lancaster, Ronald Press, New York, 1955. $10.00.

Reviewed by B. H. JENNINGS
Northwestern University

The authors state that their book is intended as a comprehensive work for aeronautical engineers, mechanical engineers, and all others concerned with the thermodynamics and flow phenomena that determine the performance of gas-turbine power plants in aircraft. It appears that they have succeeded in meeting their objectives, for the book is well written, has good diagrams, clear nomenclature, and well-chosen illustrative material.

The cycle analysis of the gas turbine is well presented, but quite brief. The chapter on flow of compressible fluids in tubes and passages is more extensive and gives some consideration to the problems of shock patterns which can arise during flow. Although the chapters on compressors, turbines, and combustion are very brief, the authors have prepared a very comprehensive chapter on analyses of gas-turbine performance in which they make use of a variety of dimensionless parameters.

The last chapters present control problems for aircraft performance analysis, followed by a historical summary of the subject. A few problems for solution are given at the end.

The authors have not endeavored to develop this book as a research monograph and specific references to the literature and to sources of data are at a minimum. The book should be useful as a text and reference for people active in this field.

Spontaneous Ignition of Liquid Fuels, by B. P. Mullins, AGARDograph no. 4, Interscience, 1955, 117 pp. $2.75.

Reviewed by IRVIN GLASSMAN
Princeton University

This AGARDograph presents an admirable survey of the present status of that part of combustion concerned with spontaneous ignition. Unlike most earlier publications on this subject, the presentation here is made with the full realization that the spontaneous ignition temperature is not a uniquely defined property. By reference to the Arrhenius reaction rate equation, the author describes the ignition process as a case of a chemical reaction that is self-accelerated to a condition of deflagration. This self-acceleration can occur either by a purely adiabatic heating process or by isothermal chain reaction. The theoretical chapter provides an explanation of the thermal and chain mechanisms for spontaneous ignition, together with relations derived from such theories for the dependence of ignition delay on pressure and temperature. This material aids in the interpretation of the empirical information given in the later chapters.

Spontaneous ignition temperature data under various test conditions are listed for 433 substances. The test methods used to obtain these data are described in individual chapters. Other sections deal with the effect of fuel additives and the application of the results. Many results are based upon the novel flow technique developed by the author for measuring ignition delay times. Unfortunately, not all of the data obtained by this method which have appeared in the journals are reported in this text.

Many engineers in the combustion field will find this AGARDograph a very useful source book.

Collected papers on Aviation Medicine, AGARDograph no. 6, Butterworths Scientific Publications, London, Interscience Publishers, N. Y., 1955, 215 pp. $5.

Reviewed by DAVID G. SIMONS
Aero Medical Field Laboratory,
Holloman Air Development Center

All but three of the eighteen papers were presented at the September 1953 meeting of the Aeromedical Panel of the Advisory Group for Aeronautical Research and Development. The contributions, in both English and French, represent six NATO nations. Topics range from broad concepts of the nature and place of aviation medicine to detailed reports of experimental research. The volume is highly recommended as a source for general aviation medical information related to current operational problems and concepts. All references to space medicine were parenthetical except the brief review of rocket studies of animal responses to weightlessness by Benson.

The collection begins with three general papers. Bergeret points out the increasingly electronic complexion of aviation medical research. This is later corroborated by a 33-page review of recent advances in instrumentation by contributors from the Lovelace Clinic. Lee-Potter introduces a competent summary of the current state of development of all branches of aviation medicine by defining it as "...the protection of flying personnel against the stresses of their environment." Benson emphasized the urgent need to delineate the human factors in the *early* design phases of aircraft weapons systems.

Two well-illustrated, clearly written, experimental research papers are included. A wealth of human, chimpanzee, and hog experiments are cited by Stapp to document tolerance limits to abrupt decelerations. Protocols and tabular data of animal experiments which form the basis of definitive human experiments are published here for the first time. The conclusion states "...tolerance limits for human subjects approximate 50*g* peaks at 500*g* per second rate of onset for 0.25 seconds duration..." with adequate restraint. Animals tolerated 80*g* and survived 200*g* with special harness while seated facing forward. The rate of change of deceleration and the body area of restraint are considered limiting factors for tolerance to abrupt deceleration. Lewis clearly shows the primary nature of cold injury discrediting the concept that injury stems secondarily from impairment of blood supply. Experiments demonstrate progressive degrees of tissue injury showing a remarkable similarity to the cell injury caused by burns.

Six papers concern clinical research. Violette observed the differences among subjects' ability to tolerate pressure breathing at 20 to 30 cm of water pressure. Monaco presented changes in respiratory rate and volume at decreased pressure. The history of the Bourdon-Wiersma Stipple test to detect latent epilepsy is reviewed by van Wulfften Palthe. He presents evidence indicating this test provokes lapses of attention in susceptible individuals, and includes a number of illuminating examples. An evaluation of the variability of night vision by Mercier is concluded by methods for improving and protecting night vision. Papers by Doesschate and Neely independently challenge the emphasis placed on tests of heterophoria in aviation medicine. Both agree that this test has limited usefulness, and should not, by itself, constitute a criterion of suitability for flight training.

The six remaining authors discussed various problems of aviation medicine. Rodahl presents a comprehensive and stimulating discussion of arctic survival problems. The physiological requirements of pressure cabins are reviewed by Roxburgh, followed by the consequences of loss of cabin pressure presented by Fryer. Phoebus indicated the increasingly urgent nature of the high-intensity noise problem in the U. S. Navy, concluding that prompt vigorous action must be taken to protect carrier deck personnel. Smith illustrates the desirability of making the job (machine) fit the man, rather than picking the man to fit the job, in a lucid analysis of the logical step by step development of an aircraft cockpit layout.

The Theory of Hydrodynamic Stability, by C. C. Lin, Cambridge Monographs on Mechanics and Applied Mathematics, The University Press, Cambridge, 1955, xi + 155 pp. $4.25.

Reviewed by W. H. REID
Ballistic Research Laboratories
Aberdeen Proving Ground, Md.

In spite of its great importance, the mechanism which governs the transition from laminar to turbulent flow is still far from being completely understood. It is only during the initial stages of transition, when the basic laminar flow first becomes unstable, that any real measure of success has been achieved. During this period in the transition process the disturbances are still so small that it is permissible to neglect their squares; this linearization, together with the "method of the exponential time factor," then leads to the famous disturbance equation of Sommerfeld and Orr (1906–1908). This equation is linear but, even so, the analysis can become extremely complicated, even controversial, at times. To adequately sum-

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marize such a subject is no mean task, and on the whole Professor Lin, whose own researches in the subject since the Second World War have greatly advanced the theory, succeeds quite well.

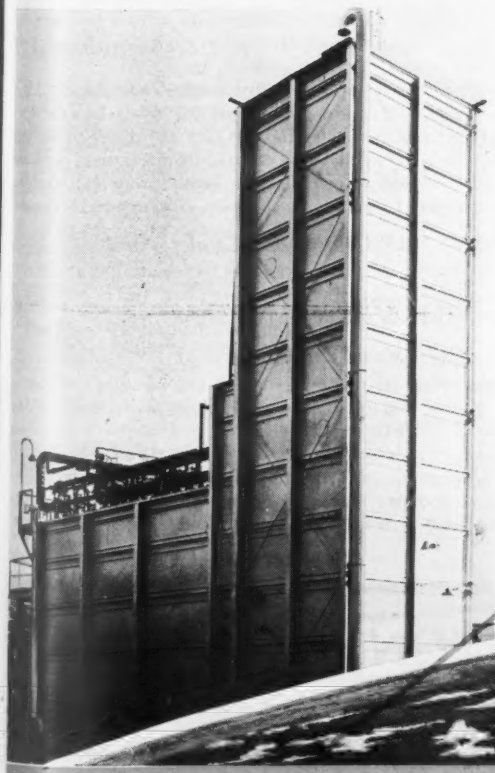
Considerable space is devoted to G. I. Taylor's early work on the stability of flow between rotating concentric cylinders, the noncontroversial nature of which makes it particularly well suited to illustrate the type of instability which arises from centrifugal forces. Anyone who has seen this experiment performed in the laboratory can hardly fail to be impressed by the sudden change, at a critical Reynolds number which Taylor predicted, from the basic two-dimensional laminar flow in which the streamlines are simply concentric circles to a three dimensional cellular flow whose structure was also computed by Taylor.

Turning next to the case of strictly parallel flows, first considered by Heisenberg in 1924, Professor Lin discusses in some detail the problem of plane Poiseuille motion, the instability of which is by now beyond question. This particular problem is of importance because it serves as the prototype for the technically important nearly parallel flows of the boundary layer type, the instability of which was first considered by Tollmien in 1929 and later by Schlichting (1933–1935). But it was not until 1940—when Schubauer and Skramstad in their now classical work on the problem were able to observe experimentally the amplified oscillations predicted theoretically by Tollmien and Schlichting—that the small disturbance theory became generally accepted. Subsequent work by Lin (1945) and others has done much to clarify most of the basic mathematical difficulties of the problem. The application of a theory developed for strictly parallel flows to nearly parallel flows of the boundary layer type clearly requires some justification; it is somewhat unfortunate, therefore, that no details of this justification are given.

In so small a book it was inevitable that some topics would be entirely omitted and that others would be treated only briefly. But what is even more regrettable is that the discussion of those topics which form the substance of the book—the stability of Couette and plane Poiseuille motion, the stability of the boundary layer over a flat plate, the physical mechanism of instability and certain detailed mathematical aspects of the theory—should have been treated in so concise a manner. This does not make for easy reading, particularly for someone coming to the subject for the first time, but careful study by those who are seriously interested in the subject will be amply rewarded.

Book Notice

Compact Heat Exchangers, by W. M. Kays and A. L. London, The National Press, Palo Alto, Calif., 1955, 156 pp. This is a compilation of analytical and experimental work concerning compact heat transfer surfaces. The material is described concisely and much of it is presented in tables and charts. This publication should be useful to heat exchanger designers.



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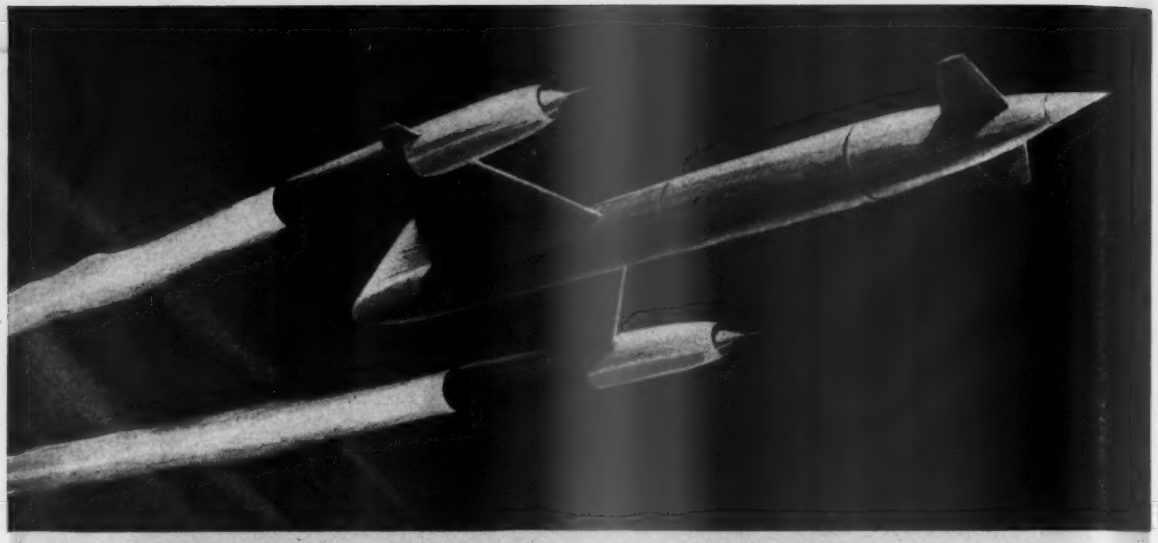

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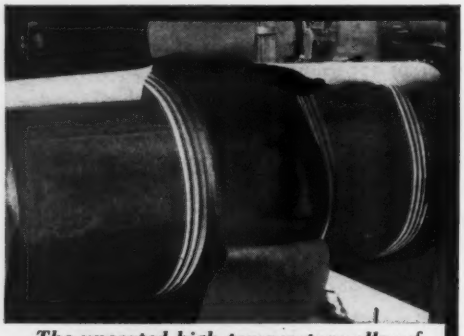

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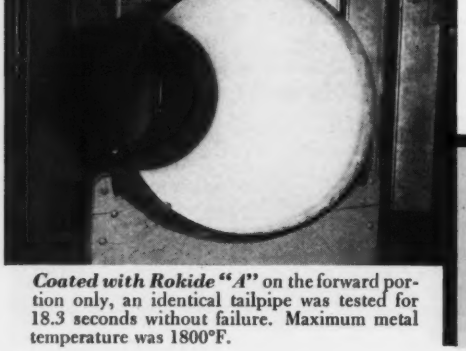

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Jet Propulsion Engines

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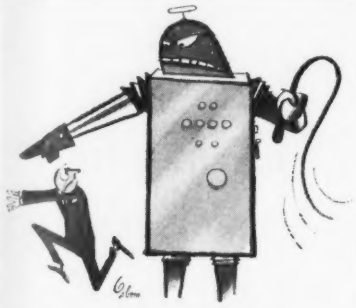

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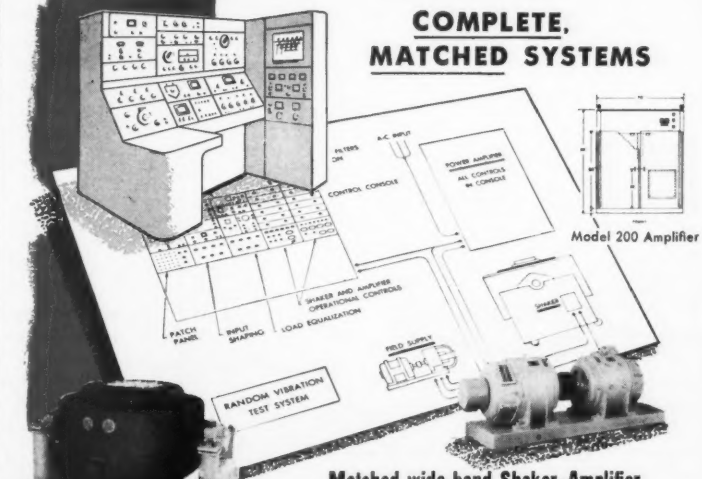

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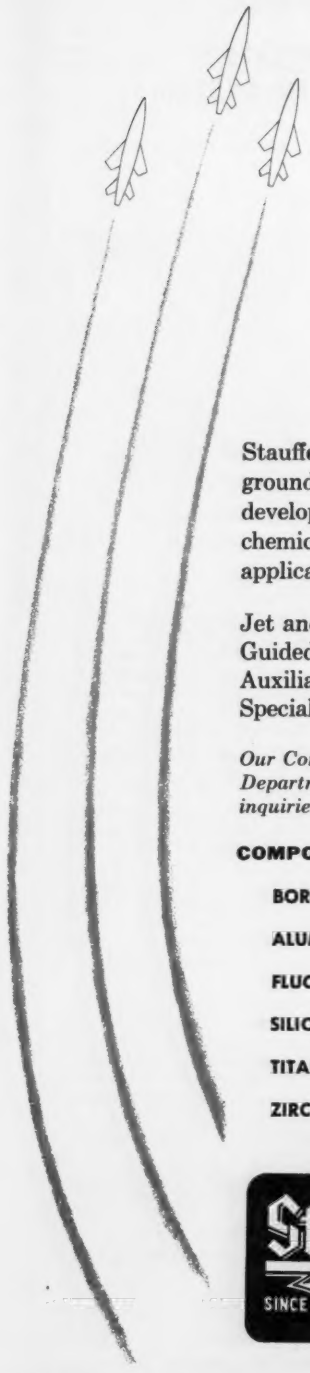

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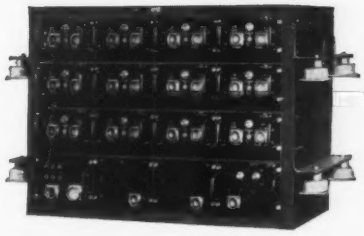

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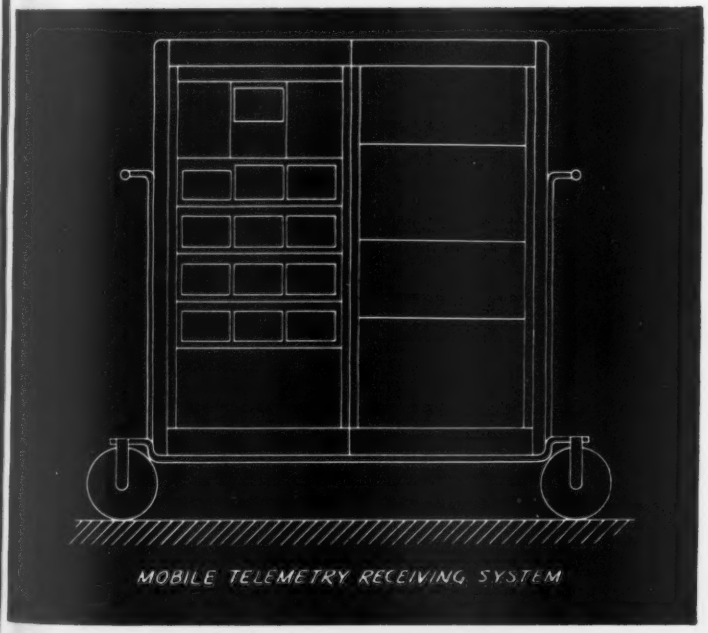

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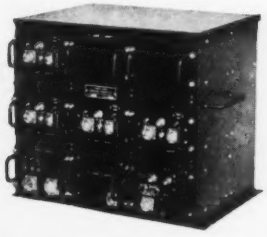

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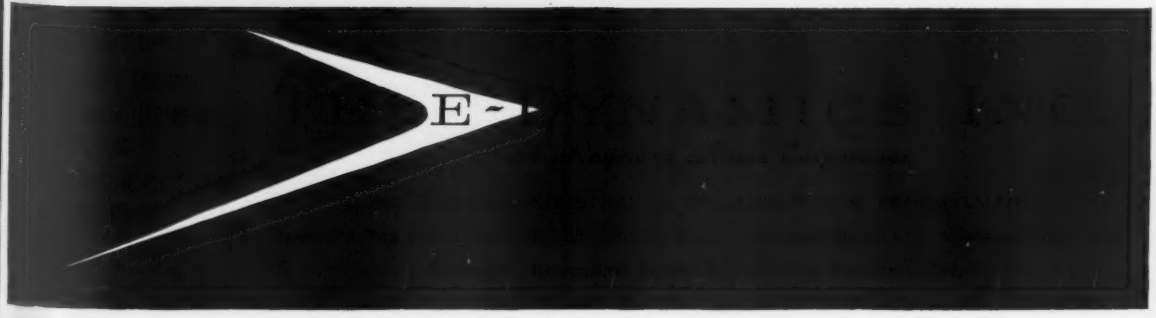

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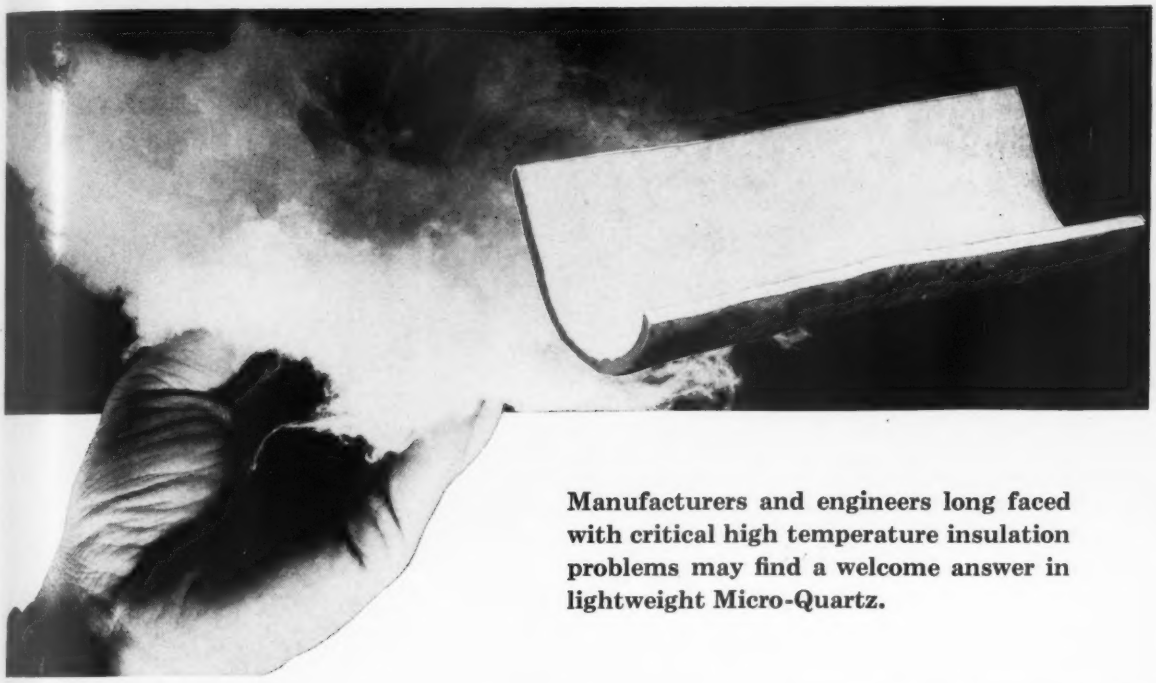

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Thickness of sheet—Standard nominal thickness is 3/16 inches

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Length of sheet—71 inches

*Other thicknesses and densities are available. Sheets can be fabricated to fit your application.

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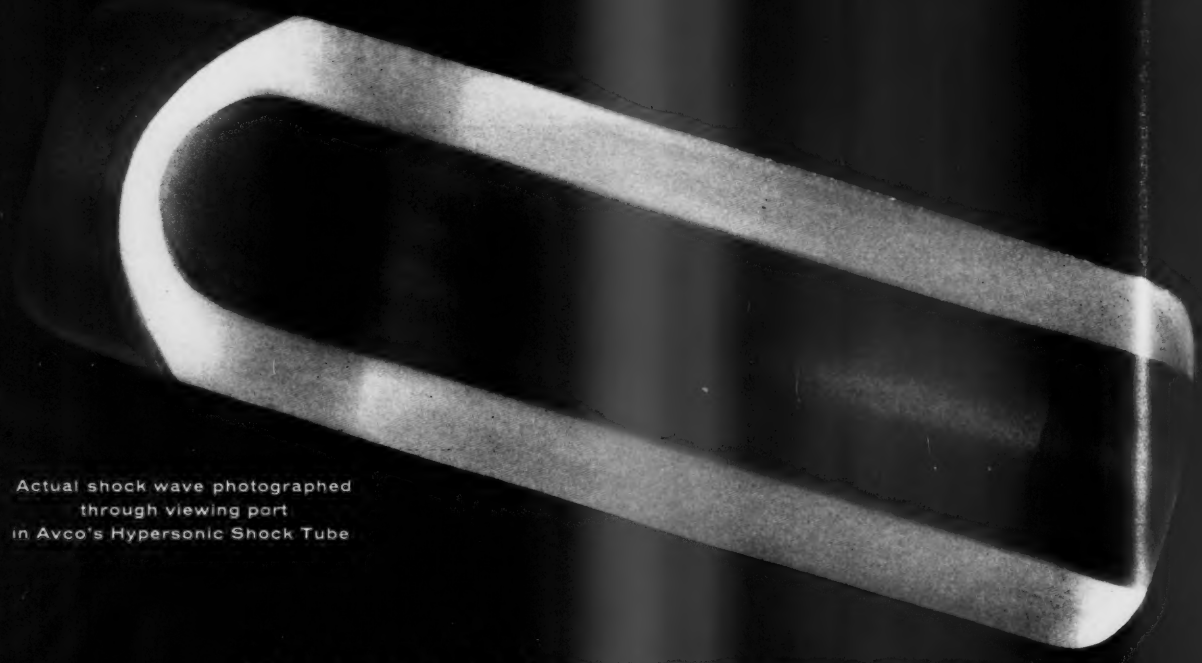

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